A MANUAL FOR CALCULATING THE CAPACITY OF A LAKE FOR DEVELOPMENT

October, 1974

Ministry of the Environment

Ontario

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FOR DEVELOPMENT

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TABLE OF CONTENTS

ABSTRACT

A technique is presented for calculating the capacity of a lake for development based on quantifiable relationships between nutrient inputs and water quality parameters reflecting lake trophic status. From the land use and geological formations prevalent in a lake's drainage basin, the phosphorus exported to the lake in run-off water can be calculated, which, when combined with the input directly to the lake's surface in precipitation and dry fallout, gives a measure of the natural total phosphorus load. From the population around the lake, the maximum artificial phosphorus load to the lake can be calculated and can be modified according to sewage disposal facilities used, if such alteration is warranted. The sum of the natural and artificial loads i.e. the total load to the lake can be combined with a measure of the lake's morphometry expressed as the mean depth, the lake's water budget expressed as the lake's flushing rate, and the phosphorus retention coefficient of the lake, a parameter dependent on both the lake's morphometry and water budget, to give a prediction of the springtime total phosphorus concentration in the lake. The latter prediction is based on a model reported by Vollenweider (1969). Long-term average runoff per unit of land area, precipitation and lake evaporation data for Ontario provide a means of calculating the necessary water budget parameters without expensive and time-consuming field measurements. The predicted spring total phosphorus concentration can be used to predict the average chlorophyll a concentration in the lake in summer, and this, in turn, can be used to estimate the Secchi disc transparency. Thus, the effects of an increase in development on a lake's water quality

can be predicted. Conversely, by setting limits for the "permissible" summer average chlorophyll _a_ concentration or Secchi disc transparency, the "permissible" total phosphorus concentration at spring overturn can be calculated. This can be translated into "permissible" artificial load, which can then be expressed as total allowable development. This figure can be compared to the current quantity of development and recommendations made concerning the desirability of further development on the lake.

LIST OF TABLES

LIST OF FIGURES

GLOSSARY OF SYMBOLS

Symbol	Meaning	Dimensions
A_o	lake area	L^2
$\bar{z}$	mean depth	L
V	lake volume	L^3
D_L	development of shoreline	-
A_d	drainage basin area	L^2
r	unit runoff	$L\ T^{-1}$
Pr	precipitation	$L\ T^{-1}$
Ev	lake evaporation	$L\ T^{-1}$
Q	total lake outflow volume	$L^3\ T^{-1}$
q_s	areal water load = Q/A_o	$L\ T^{-1}$
ρ	flushing rate	T^{-1}
τ_w	flushing time = $1/\rho$	T
R	phosphorus retention coefficient for lake	-
σ	phosphorus sedimentation rate	T^{-1}
L	loading	$M\ L^{-2}\ T^{-1}$
L_{perm}	"permissible" loading	$M\ L^{-2}\ T^{-1}$
L_E	loading from virgin drainage area	$M\ L^{-2}\ T^{-1}$
L_{PR}	loading from precipitation	$M\ L^{-2}\ T^{-1}$
L_N	natural loading = $L_E + L_{PR}$	$M\ L^{-2}\ T^{-1}$
L_A	artificial loading	$M\ L^{-2}\ T^{-1}$
L_T	total loading = $L_N + L_A$	$M\ L^{-2}\ T^{-1}$
J	supply	$M\ T^{-1}$
J_{perm}	"permissible" supply	$M\ T^{-1}$
J_E	supply from virgin drainage area	$M\ T^{-1}$

Symbol	Meaning	Dimensions
J_{PR}	supply from precipitation	$M\ T^{-1}$
J_N	natural supply	$M\ T^{-1}$
J_A	artificial supply	$M\ T^{-1}$
J_T	total supply	$M\ T^{-1}$
N_C	number of cottages	-
N_D	number of permanent dwellings	-
N_{CY}	total capita-years per year	capita-years yr^{-1}
N_{ADD}	additional "permissible" cottages	-

INTRODUCTION

The demand for summer cottaging and other recreational facilities in Ontario is increasing rapidly, with about 10,000 new cottages under construction in each year (Dept. of Tourism and Information). Governmental personnel (planners, biologists, engineers) having responsibilities of evaluating and subsequently approving or rejecting proposed developments are faced with the difficult task of effecting decisions without guidelines which quantitatively determine the effects or impacts of such development on the quality of the aquatic and terrestial environment. It must be stressed that the decisions made most assuredly have a direct effect on that quality. Suitable guidelines must be based on predictive ecological and social theories which, to date, have not been formulated in terms of practical management tools. It is the aim of this manual to provide a means of determining the capacity of a lake for cottage or permanent home development. Assuming that specific acceptable limits can be established for a number of parameters which reflect the quality of the aquatic environment, translation of these limits to permissible cottage numbers or other development schemes can be achieved through application of techniques described in this manual. Conversely, if a decision is made to allow the development of a given number of cottages or large-scale condominiums, then the governmental agency responsible will be completely cognizant of the environmental ramifications of their decision.

At this time, only the problem of lake trophic status is considered, with the equally important concerns of the effects of development on fisheries, wildlife and on human health not taken into account (there is, of course, considerable relationship between trophic

state and fisheries potential.) It should be stressed that the approach described herein is intended to serve as an interim solution until the results of the Lakeshore Capacity Study (which is currently being undertaken by personnel of Ministry of the Environment and Ministry of Natural Resources), have been obtained and translated into management principles. This latter study will take cognizance of health, fisheries and wildlife, as well as trophic status, in assessing the impact of development on watersheds.

In understanding lake conditions, it is important to realize that the entire watershed and not just the lake or the lake and its shoreline, is the basic ecosystem unit. The terrestial and aquatic portions of any watershed are inherently linked with the gravitational movement of minerals in drainage waters flowing from the land to the water (ie. lakes, oceans), as the major terrestial-aquatic linkage (Likens and Bormann, 1974). It is important to note that the aquatic portion of a watershed is "downhill" from the terrestial portion; that is, dissolved and particulate material from the land are transported by geological processes to the water and eventually to the less accessible sites of the sediments in the aquatic portions of the ecosystem. There is, of course, some "uphill" movement of material by meteorological and biological transport, eg. release of N_2 from a lake through denitrification and gas diffusion, followed by precipitation of the same to the land for the former process, and movement of material through the food chain for the latter (Figure 1). However, the <u>net</u> movement is always "downhill", ie. <u>to</u> the aquatic system, with the deficit made up by geological weathering of rocks. The implication of this in terms of a lake's capacity for development is that <u>any alteration in a watershed ultimately, through</u>

a complicated series of terrestial-aquatic linkages, effects the lake. Thus, any management approach based solely on the lake and its shoreline is both simplistic and inaccurate.

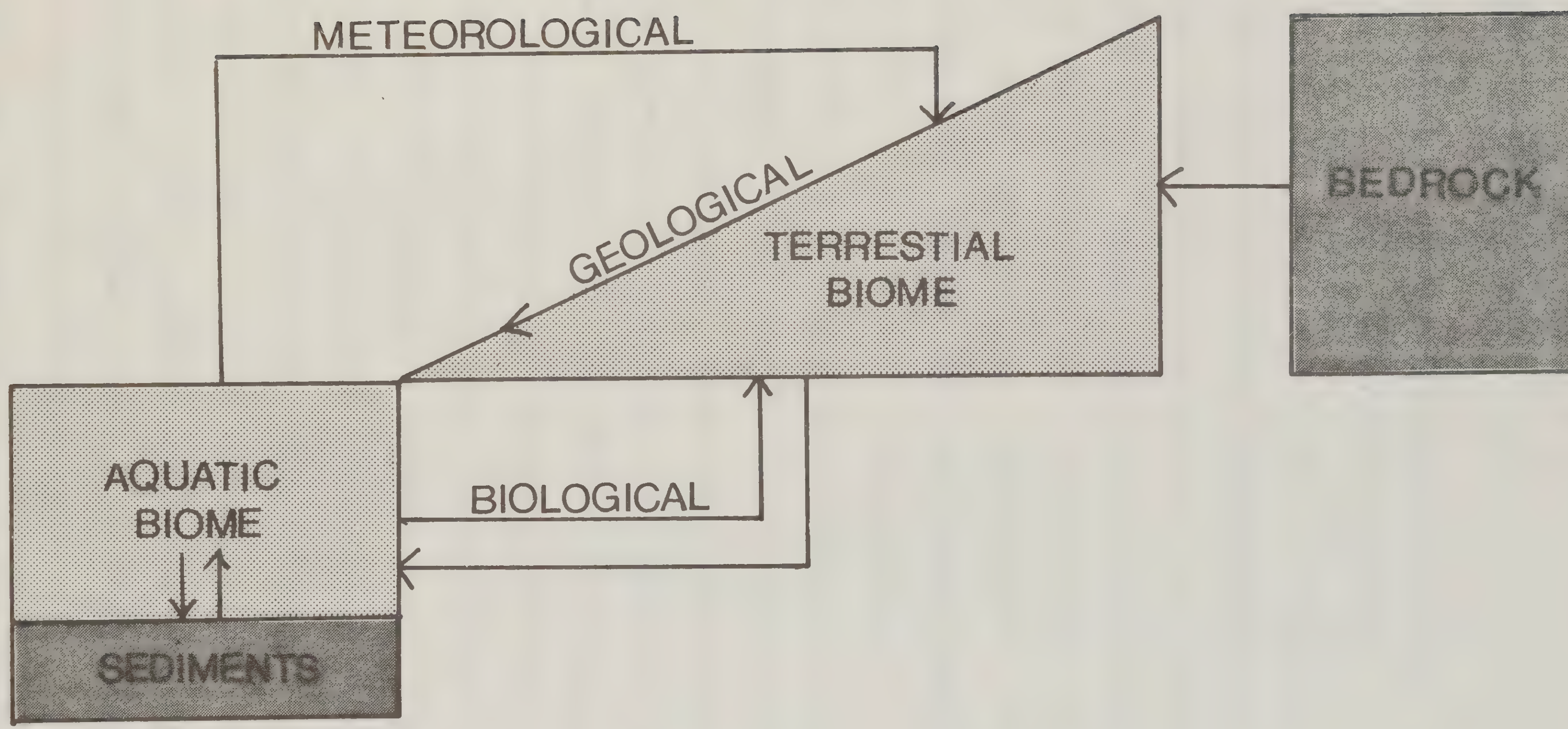

Figure 1: Pathways of terrestial linkages.

BACKGROUND FOR A TROPHIC STATUS INDEX

Historical Development

As stated in the Introduction, adequate watershed management can only be based on quantitative predictive ecological theories. Very few useful models or theories are available to the planner at the present time because ecology has been largely a descriptive science with too little attention given to predictability. Emphasis must now be directed to the development of models whose value will be judged on their predictive ability alone. Under these conditions, empirical models are as valid as realistic models provided they make testable predictions about the effects of various stresses on the environment.

Early empirical approaches were directed almost exclusively to fisheries management in the sense of potential yields or production rather than to lake trophic state. Rawson (1952, 1955) related the 25-year average commerical fish production for a number of large Canadian lakes to mean depth - an index of the lake's morphometry (Figure 2), a parameter recognized by Thienemann (1927) many years before as one of the most important factors controlling lake productivity. Moyle (1946) related fish production in Minnesota to total alkalinity and total phosphorus content; Rounsefell (1946) found an inverse relationship between lake surface area. Hayes and Anthony (1964) combined the above approaches, relating fish yield to lake area, mean depth and alkalinity. Other researchers, notably Larkin and Northcote (1958), Hrbaček (1969), and Reimers, Maciolek and Pister (1955), also investigated and reported similar relationships.

In 1965, Ryder introduced what is now the most popular method of estimating potential fish production, the morphoedaphic index. This index, determined as the total dissolved solid concentration divided by

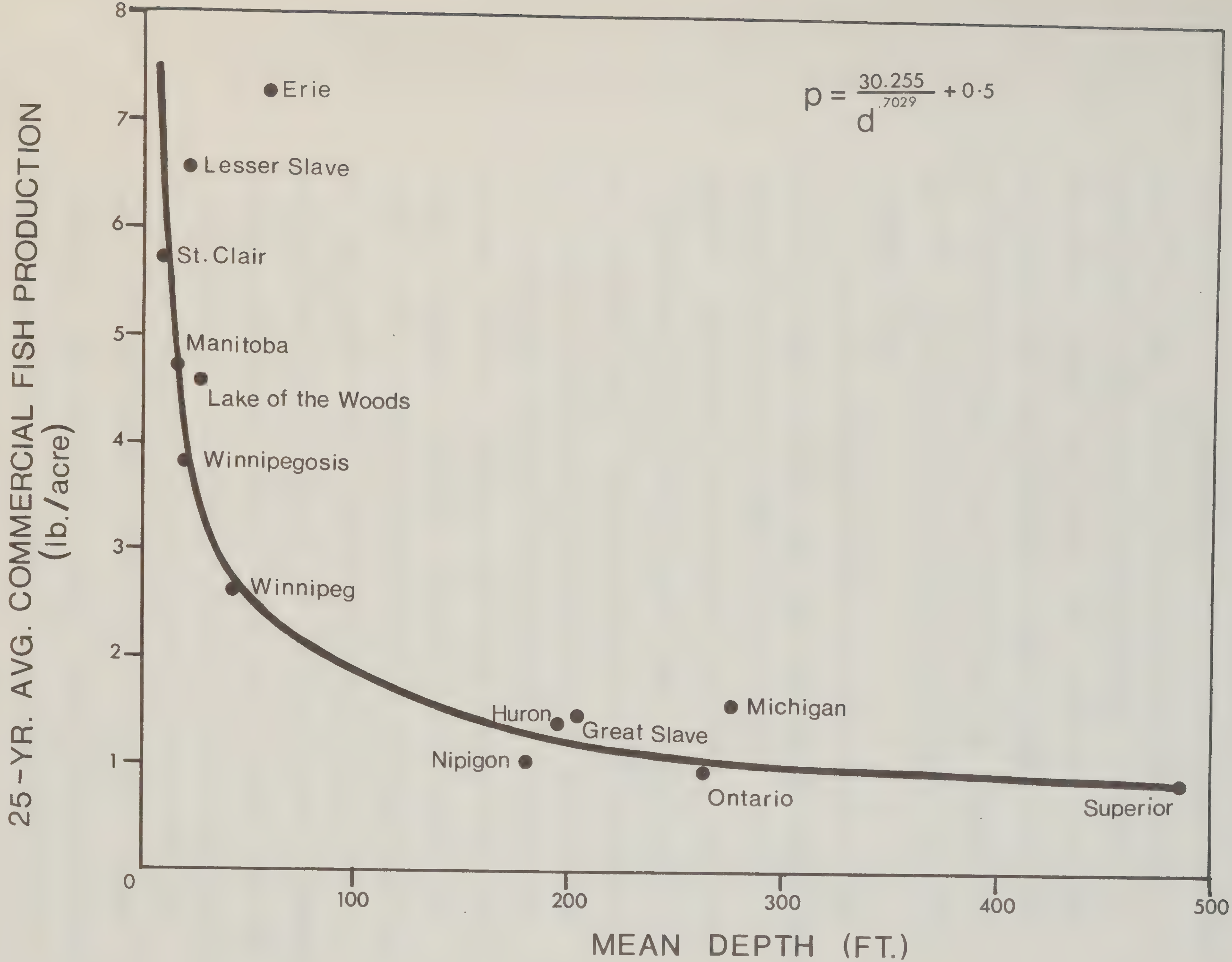

Figure 2: Rawson's relationship between 25 year average fish harvest and mean depth (from Rawson 1955).

lake mean depth, was highly correlated to fish production for 23 Canadian lakes. The morphoedaphic index has been further investigated by Jenkins (1968, 1970) and has been found to be suitable for a wider range of lakes than the original selection. The most satisfactory aspect of this index is that a prediction can be made for potential fish yield from only two simple parameters, the total dissolved solids content and mean depth of the lake. However, this approach is not suitable for determining how development will effect a potential yield.

Although considerable attempts to manage fisheries by the empirical approach have been tried, very little has been accomplished in terms of managing development by a similar method. A notable exception was Seppanen's (1972) proposal to determine a lake's summer cottaging capacity. The author suggested that a suitable formula for the recommended number of shoreline cottages was $\frac{A \cdot \sqrt{D_L}}{10}$ where A is the lake area in hectares, D_L is the development of shoreline equal to the shorelength divided by the circumference of a circle of the same area, and 10 is a figure representing the minimum area of lake surface (in hectares) needed per cottage for a round lake with no islands. While providing a formula that takes into account both lake area and shoreline length, many other important factors are neglected making the technique quite limited for its intended purpose. Presently, in Ontario, governmental approval or rejection of a resort development is determined, in part, through application of individual components of the Lake Alert Study (Hough, Stansbury and Assoc. Ltd. 1972). The simplest and most frequently used procedure, the BOAT/LIMIT system, is based on a requirement of 3.3 acres of "usable" lake surface (usable in terms of power boating) per cottage. A much more sophisticated

system is also outlined, the SCORE/MAP system. Under this scheme constraints are mapped for the shoreline based on water quality, fish and wildlife, vegetation, soil, scenic elements, boating, access, private lands, and public outdoor recreation. However, the relative importance of each of these factors must be arbitrarily decided and a weighting factor employed. The constraints are summed and an arbitrary cutoff point is determined. Using a minimum lot size guideline, the acceptable shoreline is divided and the minimum of either this number or the boat limit result is termed the acceptable total development. Considering the water quality aspects of Lake Alert, six parameters (mean depth, oxygen distribution, chlorophyll *a* concentration, Secchi disc, iron:phosphorus ratio, and morphoedaphic index) were measured; the resultant values were scored between 0 and 10. The sum (0-60) was then ranked along with other constraining parameters. The shortcoming of this approach is that no *predictive relationship* between development and potential water quality (or any other parameter) can be made, ie. a calculation that a given lake has a capacity for 200 additional cottages does not include any prediction of how those cottages will effect water quality or any of the other constraining parameters. The Lake Alert scheme is, in fact, based on qualitative rather than quantitative evaluation.

An entirely different and far-reaching, although somewhat indirect, approach has recently been used in a lake management sense. In 1968, Vollenweider published in his classic text on eutrophication, a plot (Figure 3) of total annual phosphorus loading (the amount of material added per unit surface area of lake per annum) vs. mean depth ($\bar{z}$). Vollenweider found that bands could arbitrarily be drawn separating the lakes into the three standard lake types in terms of

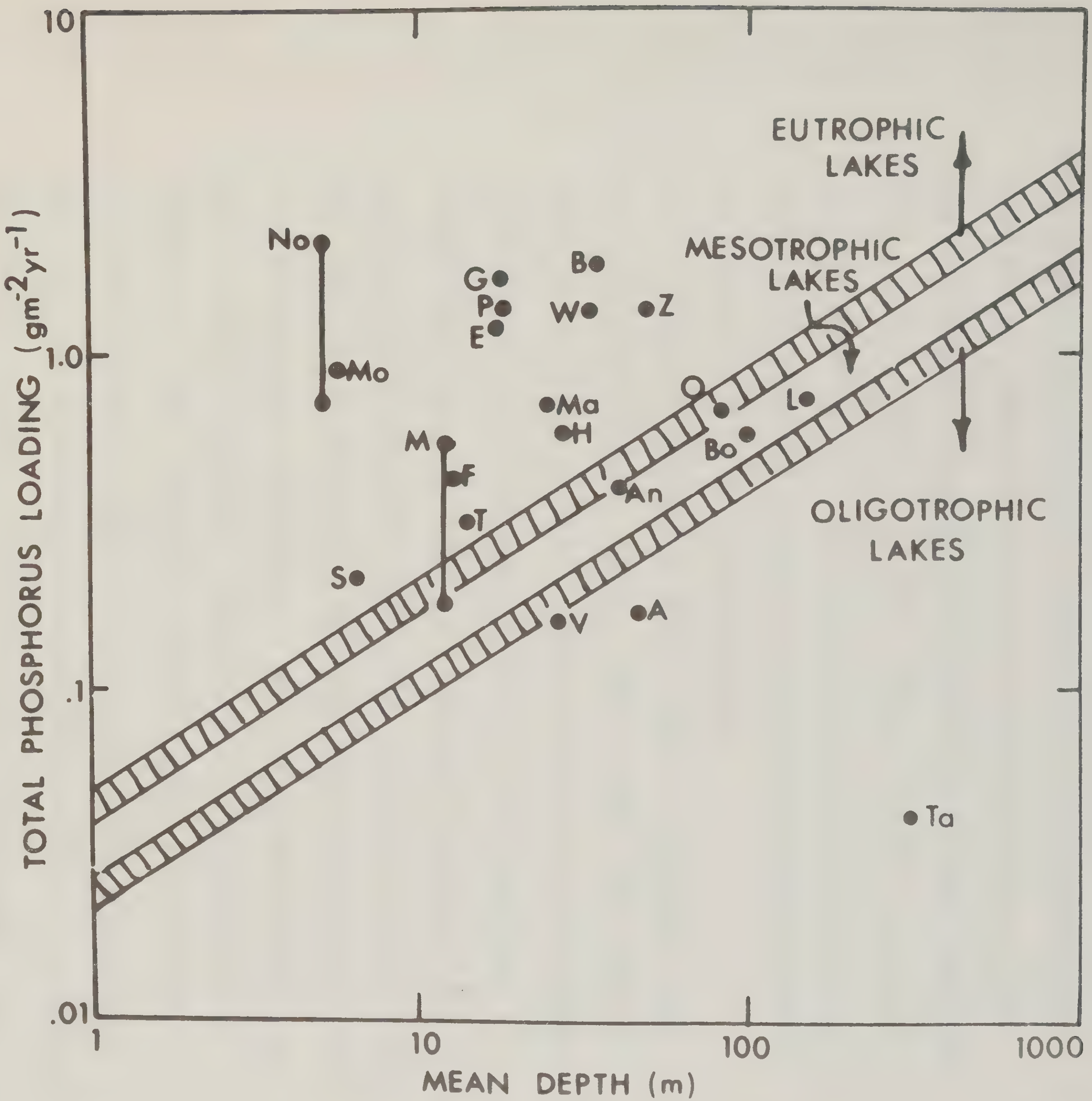

Figure 3: Vollenweider's total phosphorus loading - mean depth relationship (from Vollenweider 1968)

degree of eutrophy: oligotrophic, mesotrophic and eutrophic. The lower line separating oligotrophic from mesotrophic lakes was termed the "permissible loading" since it represented the upper loading level as a function of mean depth that could be permitted without having the lakes revert beyond the oligotrophic state, while the upper line, the "critical loading", represented the level above which a lake could be characterized as eutrophic. A similar relationship was derived for nitrogen loading assuming a tolerable N/P ratio of 15:1 (by weight).

Faith in this simple model stemmed from the fact that for lakes with phosphorus loading data available, the predicted status in most cases matched the observed status as exemplified by the standard (but arbitrary) criteria of lake condition: transparency (Secchi disc depth), chlorophyll _a_ concentration, oxygen concentration in the hypolimnion, frequency of algal blooms, etc. This simple relationship has been widely accepted both as a guide to the degree of eutrophy of lakes and, more important, as a guide to the "permissible" and "dangerous" loading levels of phosphorus to lakes (Schindler and Nighswander 1970; Schindler _et al_ 1971; Gächter and Furrer 1972; Patalas 1972; Patalas and Salki 1973; Ahl 1972; Stumm and Stumm-Zollinger 1972; International Joint Commission 1969). Perhaps the most important use of this relationship was to provide a rationale for the removal of phosphorus from sewage treatment effluent in the Laurentian Great Lakes. For example, Lake Ontario, in the mesotrophic category according to its estimated total phosphorus loading for 1967, would, in 1986, fit into the oligotrophic range of the graph if 95% of the phosphorus was removed from all municipal and industrial wastes. However, without phosphorus control, Lake Ontario would, according to Figure 3 be well into the eutrophic range in 1986. By a similar argument, Lake Erie,

well in the eutrophic range in 1967, would be improved almost to the mesotrophic category in 1986 with phosphorus control or would be even more eutrophic without control. In much the same way, if a lake's phosphorus loading is measured or calculated, the additional load required to maintain a given trophic status level can be calculated and loosely interpreted in terms of capita-years; this calculation in turn may be translated into cottages or additional capacity for development.

The first reported case of lakes which clearly did not fit Vollenweider's phosphorus loading - mean depth characterization was described by Dillon (1974a,b). In a study of the total phosphorus budget of 19 lakes in southern Ontario, it was found that a number of lakes had very high phosphorus loadings (5 lakes with $L>1$ g m^{-2} yr^{-1}). According to Vollenweider's relationship, many of these lakes should have been eutrophic, yet in all cases the chlorophyll a concentrations were low (summer averages between 0.8 and 2.7 mg m^{-3}), Secchi disc depths were high (summer averages, 3.5 - 8.7 m) and significant hypolimnetic oxygen deficits were not formed. The reason for this discrepancy was undoubtably that many of these lakes had very high flushing rates resulting from the large drainage area/lake area ratios.

In 1973, Vollenweider modified his relationship to take such lakes into account. This was accomplished by incorporating the mean residence time of the water in the lake (τ_w). By plotting L vs. $\bar{z}/\tau_w$, (Figure 4), a more realistic representation was achieved. The parameter $\bar{z}/\tau_w$ is equivalent to the areal water loading (ie. the height of the water load over the lake's area that is supplied in one year). The L vs. $\bar{z}/\tau_w$ model has been used for predicting changes in trophic status of several Muskoka Lakes (Michalski, Johnson and Veal

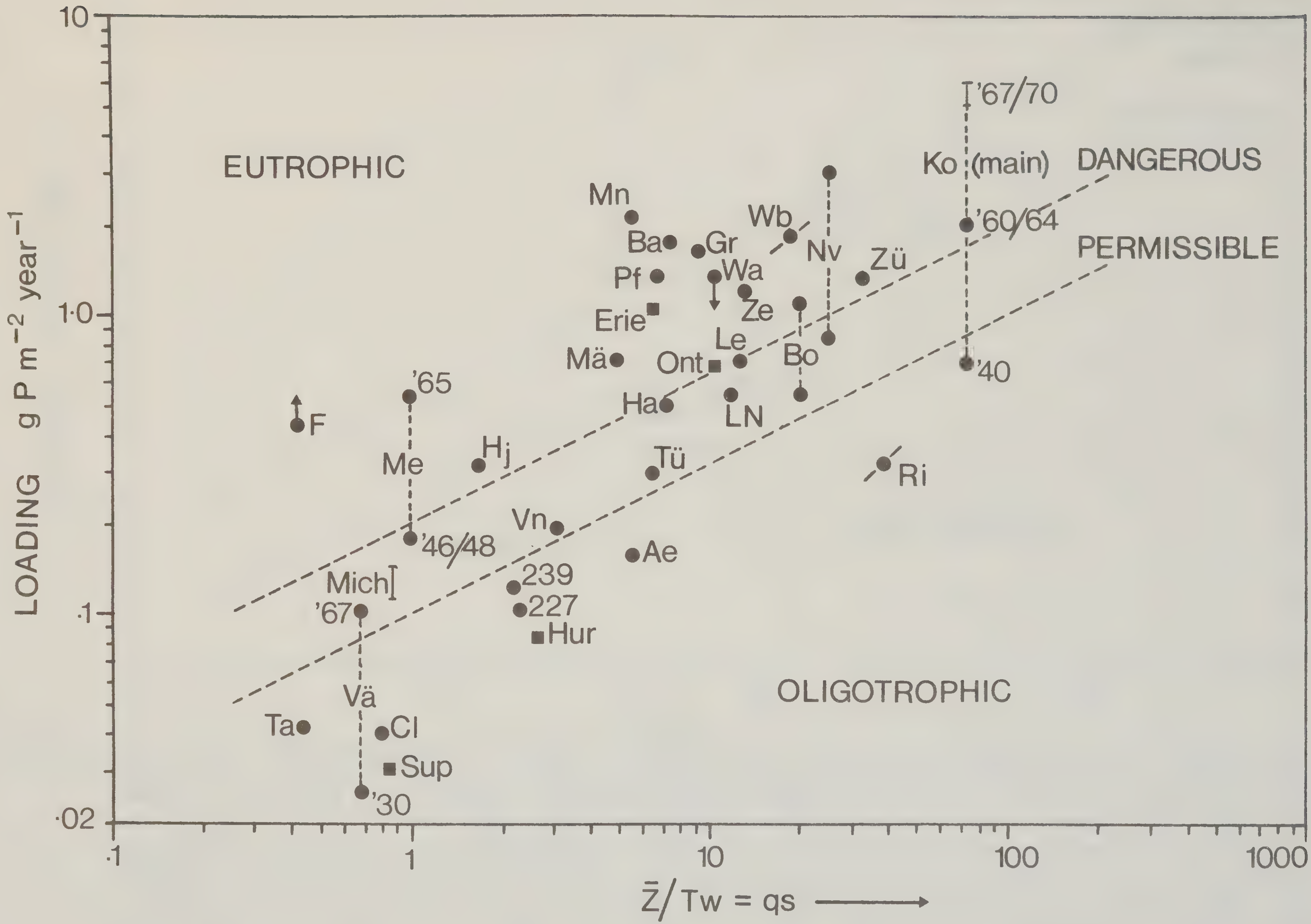

Figure 4: Vollenweider's total phosphorus loading - mean depth divided by flushing time relationship (from Vollenweider 1973. See original paper for details.)

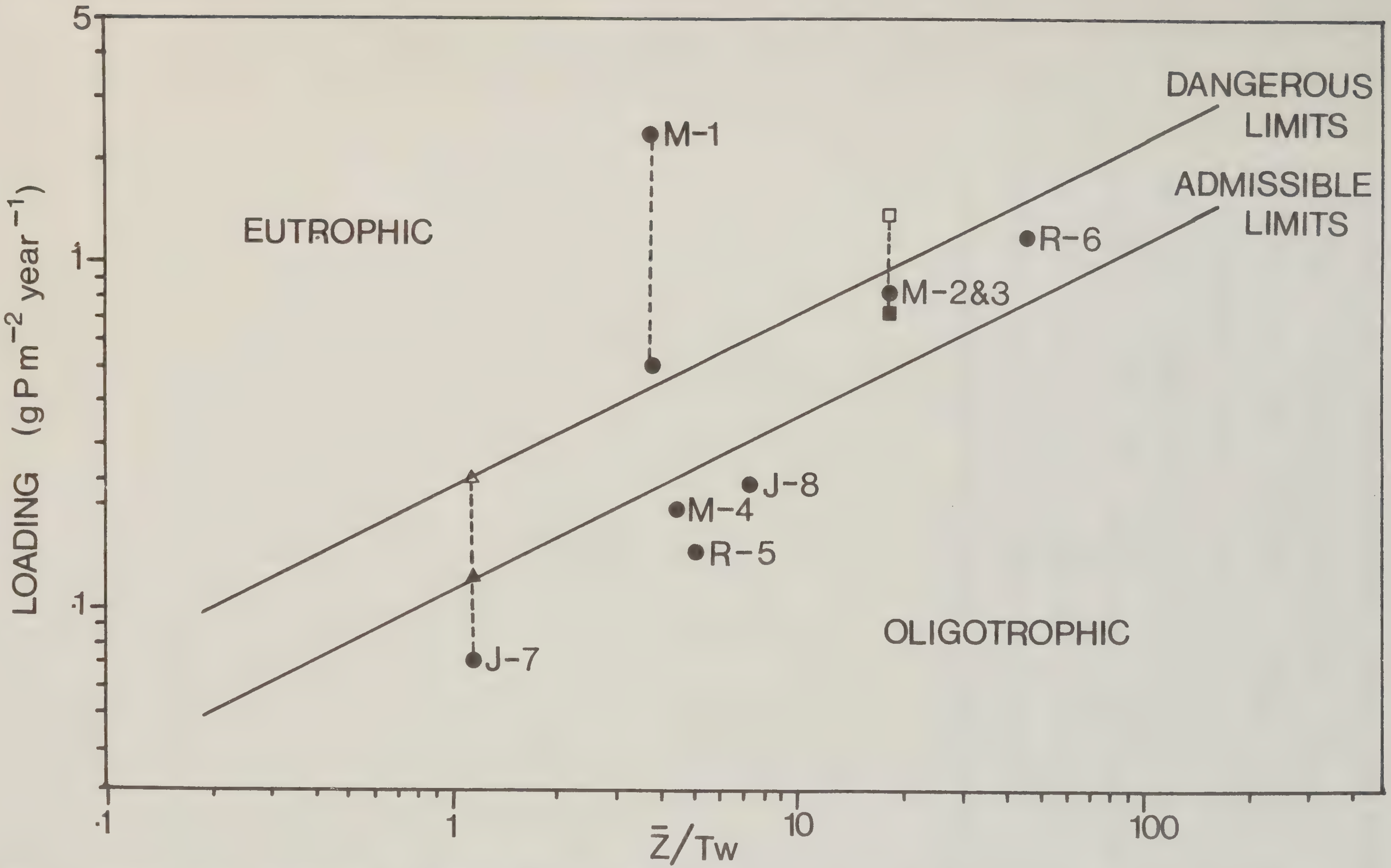

Figure 5: Annual total phosphorus loadings (closed circles) to Lakes Joseph (J-7), Rosseau (R-5) and Muskoka (M2 and M3), Dudley (M-4) and Gravenhurst (M-1) Bays and to Little Lake Joseph (J-8). Loading rates and clarification of the degrees of eutrophy (i.e. diagonal lines) are after Vollenweider (in press). Lakes above the upper diagonals are eutrophic in status while lakes below the diagonal are oligotrophic. Lakes between the diagonals are mesotrophic. The open circle represents the "measure of eutrophication" for Gravenhurst Bay following 85% reduction of phosphorus from the Gravenhurst and Ontario Hospital Sewage Treatment Plants. The closed and open triangles represent the positions of Lake Joseph following population increases of 1,150 and 4,400 capita-years, respectively. The open square depicts the eutrophic status of Muskoka Lake with twice the current population. The closed square represents a slightly improved trophic status in relation to the lake's present position assuming 85% phosphorus removal for the aforementioned increased population as well as for current shoreline residents.

1973) that would result from changes brought about by the reduction of phosphorus in sewage effluent (Figure 5). As effected by Michalski _et al_ (1973), the model can be employed by environmental managers in the same manner as the L vs. $\bar{z}$ plot: the maximum additional loading to a lake that will not surpass the "permissible" loading can be calculated and interpreted in terms of cottage development. Although a significant improvement over the L vs. $\bar{z}$ plot, this method still lacks quantitative predictability in terms of water quality parameters.

Basis for a New Approach

Any approach to predict water quality from a trophic status point of view must take into account the importance of the element phosphorus. That phosphorus is the nutrient most frequently controlling production and therefore trophic status in north temperate lakes has been demonstrated on numerous occasions (Schindler *et al*. 1971, Schindler 1974; Fuhs *et al*. 1972). As early as 1947, Sawyer (1947) recognized that phosphorus concentration in the lake water was the factor controlling eutrophication. Although Vollenweider's L vs. $\bar{z}$ plot relates loading rather than concentration to trophic state, his improved second relationship, L vs. $\bar{z}/\tau_w$, relates *phosphorus concentration*, and *not loading*, to trophic state. This may seem at first to be a contradiction but the rationale is as follows: the lines separating lakes into distinct trophic types have the dimensions of $L/\bar{z}/\tau_w$ or $g\ m^{-2}\ yr^{-1}/m\ yr^{-1}$, ie. $g\ m^{-3}$. Thus, the lines are independent of time and have units of concentration (the lines of the L vs. $\bar{z}$ plot have units of $g\ m^{-3}\ yr^{-1}$, ie. of *volumetric* rather than *areal* loading). Since the parameters with which one subjectively evaluates a lake (chlorophyll *a*, oxygen in the hypolimnion) are also expressed in terms of concentration, the above interpretation is most reasonable. Consequently, predictions relating the impact of development on the phosphorus concentration of a lake and subsequently on parameters describing the trophic state are central to a predictive management scheme.

The overall approach employed in this manual is shown in Figure 6. From consideration of the geology and land use of a lake's drainage basin, it is possible to estimate the total phosphorus

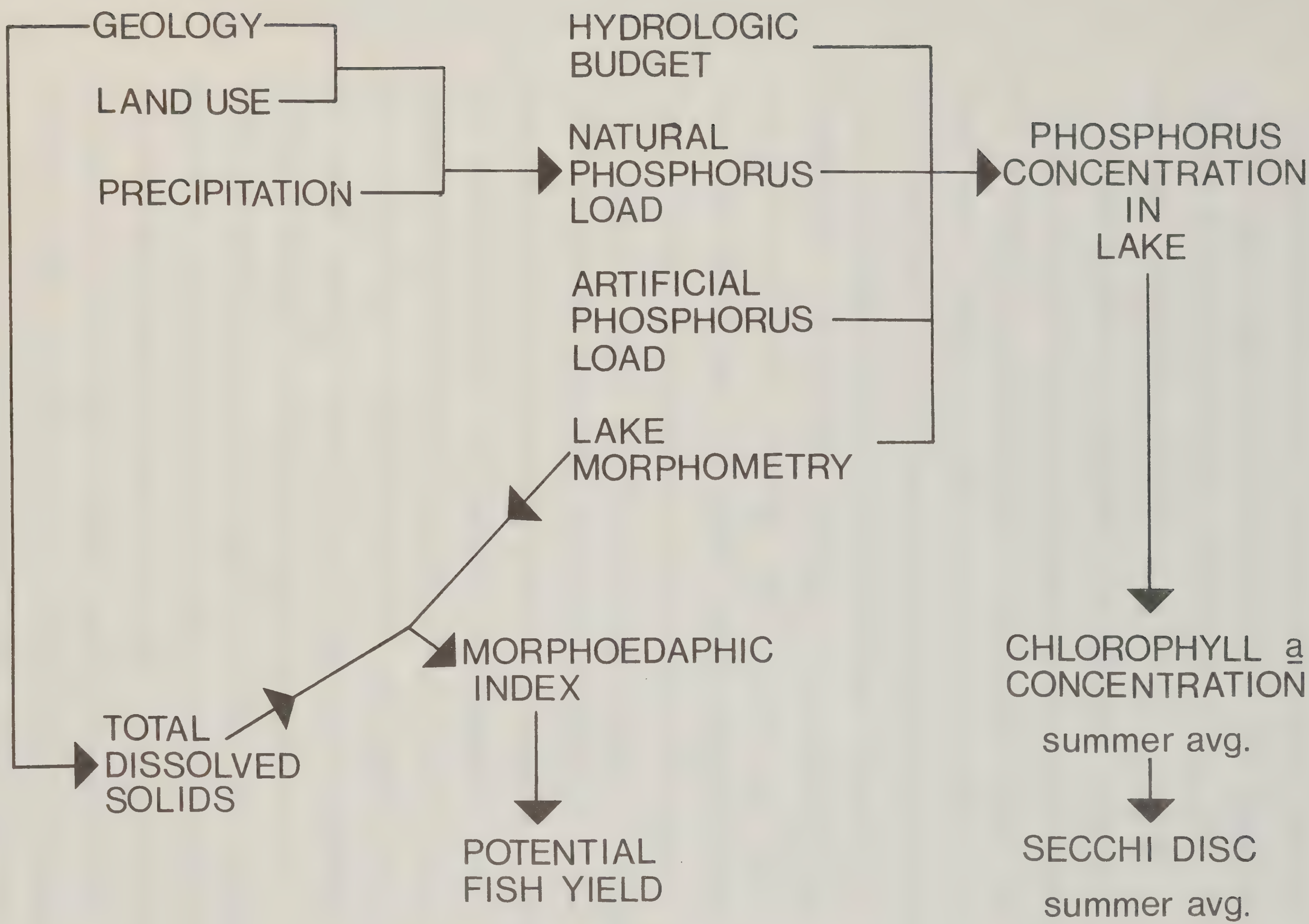

Figure 6: Scheme used in this manual for linkage of empirical models.

exported or washed out per unit area of watershed, which, combined with the drainage area provides an estimate of the total phosphorus supplied to the lake from the land. Addition of the input of phosphorus in precipitation directly falling on the lake allows calculation of the natural phosphorus load to the lake. Development existing on the lake is then measured (aerial survey or field counts) and the phosphorus loading from artificial sources calculated. The total loading, natural plus artificial, may then be combined with the lake's morphometry and water budget to predict a phosphorus concentration which is subsequently related to the average summer chlorophyll a concentration. From this latter calculation, one may determine the mean ice-free Secchi disc visibility. This manual will most often be used in the opposite sense. For example, maximum acceptable average summer chlorophyll a concentration (or minimum Secchi disc reading) will be established by the appropriate governmental agency. From these limits, decision-making personnel will be able to calculate a maximum permissible phosphorus concentration, which can be interpreted in terms of a maximum "permissible" total phosphorus load, because the lake morphometry and water budget are essentially fixed. That is, although there are year-to-year variations in the lake's water budget, the long-term average budget is acceptable. Finally, the maximum permissible artificial phosphorus loading can be estimated and expressed as the maximum allowable development (ie. numbers of cottages, etc.). Although hypolimnetic oxygen deficits have been related to phosphorus loading for the Great Lakes (Gilbertson, Dobson and Lee 1972), a direct relationship applicable to a wide variety of lakes and especially to lakes of the Precambrian Shield is not yet available. Mortimer (1941, 1942) suggested limits of 0.025 mg cm^{-2} day^{-1} for eutrophic lakes, but the quantitative

link to nutrients is, as yet, unformulated.

In addition, the potential fish yield of the lake to be considered for development can be approximated by Ryder's morphoedaphic index (TDS ÷ $\bar{z}$), but the effect of the development on future fish yields cannot. The change in TDS resulting from a change in the nutrient budget brought about by development cannot be predicted.

In the following section the theory and method for each step of the scheme are described in detail, and subsequently a stepwise procedure for calculating the lake's capacity is outlined for use by planners, managers, etc.

THEORY FOR EACH STEP OF THE MANAGEMENT SCHEME

Calculation of the Phosphorus Loading to the Lake

1. Natural Phosphorus Load (L_N)

(a) From Land (L_E)

The geological formations of southern Ontario can, as a first approximation, be classified as Precambrian igneous rock of plutonic origin (Canadian Shield) or sedimentary rock. The former is typically composed of granites, gneisses, pegmatites, syemite, migmatites, diorite, gabbro, hornblendite, amphibolite and pyroxenites, the latter of limestone, dolomite, shale and basal clastics. A very large proportion of Ontario's recreational lakes are situated on the Shield, with only the southern portion of the Kawartha - Trent system, Lake Simcoe and a few smaller lakes on sedimentary material. In addition, the watersheds of most of the Shield lakes are entirely or almost entirely forested, with the remainder being either marshland or pastureland which, although used for agricultural purposes, is not chemically fertilized. Even south of the Shield on the sedimentary bedrock, there are few areas where intensive agriculture (ie. chemical fertilization) is practised in prime recreational land; some areas around Lake Simcoe are a notable exception. Dillon and Kirchner (1974) have developed a phosphorus export scheme (Table 1) which is based on classification of geology as either "igneous" or "sedimentary" and land use as "forest" or "forest plus pasture"; the latter category implies that 15% or more of the watershed is cleared but unfertilized land. This export scheme is applicable to almost the entire recreational lake area of Ontario. The results of Dillon and Kirchner are based on a combination of a study of the phosphorus export of 34 watersheds in southern Ontario and all additional phosphorus export studies reported in the literature

Table 1: Ranges and mean values for export of total phosphorus from 43 watersheds. Results in mg m^{-2} yr^{-1}.

	Geological Classification	
	Igneous	Sedimentary
Land Use		
Forest		
Range	0.7 - 8.8	6.7 - 18.3
Mean	4.7	11.7
Forest + Pasture		
Range	5.9 - 16.0	11.1 - 37.0
Mean	10.2	23.3

where watersheds fall into the above mentioned categories. It is important to note that the natural export from sedimentary materials (off the Shield) is almost exactly double that from igneous bedrock (on the Shield); therefore, lakes such as the Kawarthas have a higher natural loading than Precambrian lakes. In addition, a change from a land use of forest to forest plus pasture doubles the export within a geological classification; for example, from 4.7 to 10.2 mg m^{-2} yr^{-1} for igneous watersheds and from 11.7 and 23.3 mg m^{-2} yr^{-1} in sedimentary watersheds. If a development significantly alters the amount of cleared land in a watershed, then an appropriate change in the export value used must be made.

To calculate the natural phosphorus loading to a lake from its drainage area, one must know the area of the watershed of each tributary to the lake, and be able to classify each as to geology and land use so that the export coefficient can be determined. Should the location be one of the few where intensive farming is undertaken, the reader should consult Vollenweider (1968), Dillon and Kirchner (1974) and Loehr (1974). The total amount of phosphorus supplied to the lake from the land is therefore calculated as the sum of the area of each drainage basin times its phosphorus export coefficient:

$$J_E = \Sigma (A_d \cdot E_i)$$

The areal loading of phosphorus supplied to the lake from the land L_E, is equal to $(\Sigma A_d \cdot E_i)/A_o$ and is equivalent to the supply divided by the lake area.

A complicating factor arises if any tributary or watershed of the lake in question has an additional lake or lakes in its course. These lakes undoubtably act as traps for phosphorus and other nutrients, decreasing the actual amount of material transported from the drainage

area to the lake in question. A means of accounting for this is described in a later section.

(b) From Precipitation (L_{PR})

Phosphorus input via precipitation (wet and dry fallout) has been virtually ignored until recent years. Studies by Schindler and Nighswander (1970), Armstrong and Schindler (1971), Barica and Armstrong (1971), Dillon (1974a), Dillon and Rigler (1974a), Kluesener (1972) and Shannon and Brezonik (1972) have demonstrated that, for many lakes, precipitation can be a major source of nutrients. From consideration of the above-mentioned studies, which found loadings ranging from 27 - 102 mg m^{-2} of lake surface yr^{-1}, a value of 75 mg m^{-2} yr^{-1} is recommended as applicable to southern Ontario lakes. Most of the lower values did not include a measure of phosphorus in dry fallout and the highest value, 102 mg m^{-2} yr^{-1}, was measured in an area where much of the land was used for agriculture. Furthermore, the figure of 77 mg m^{-2} yr^{-1} found by Dillon (1974a) was measured in the Haliburton Highlands area of the province, an area of prime concern for recreational development. Thus, a figure of 75 mg m^{-2} yr^{-1} is reasonable, although additional research is obviously needed. This topic is reviewed by Chapin and Uttormark (1973).

With L_{PR} = 75 mg m^{-2} yr^{-1}, the natural phosphorus supply to a lake (J_N) is given as:

$$\begin{aligned} J_N &= J_E + J_{PR} \\ &= (\Sigma(A_d \cdot E_i) + 75 \cdot A_o)/10^6 \qquad (\text{kg yr}^{-1}) \qquad (2) \end{aligned}$$

or the loading (L_N)

$$L_N = \frac{\Sigma\,(A_d \cdot E_i)}{A_o} + 75 \qquad (\text{mg m}^{-2}\ \text{yr}^{-1})$$

with A_o and A_d in m^2.

2. Artificial Phosphorus Load (L_A)

The calculation of the phosphorus supplied to a lake by the population in its drainage basin is a difficult task and must necessarily be based on a supply per capita-year figure with several assumptions inherent in this method. Although numerous figures are quoted in the literature (eg. see Vollenweider 1968 or Dillon 1974c for a summary) great care must be taken in selecting the appropriate value. The following points must be remembered:

a) Values measured in studies such as that of Johnson and Owen in 1971 (1.5 kg capita^{-1} y^{-1}) and used by Michalski, Johnson and Veal (1973) are no longer applicable because of legislation to reduce the phosphorus content of laundry detergents. High phosphorus content dishwashing detergents, however, remain legal and a survey of the Muskoka lakes found that 30% of the cottages in the area employed automatic dishwashers.

b) The waste disposal technique for most developments that are already established or will be established in the near future is the conventional septic tank - tile field system. The efficiency of this treatment as far as phosphorus removal is concerned is dependent on the type and depth of soil surrounding the tile bed and between the tile bed and the lake. In Precambrian areas, typically having very shallow, coarse-textured sandy or muck soils there is no satisfactory evidence which indicates that phosphorus is retained in the soils. Therefore, it must be assumed that all phosphorus discharged to soils of a tile bed area eventually gains access to the lake. In sedimentary areas, septic tank - tile field systems located in sand, gravel or muck areas are likely to be as ineffective as far as phosphorus retention is concerned as

those on systems located on the Shield. Lakes surrounded by clay or clay-loam soil, however, will be provided with some measure of protection.

c) Additional sources of phosphorus, (eg. fertilizer applied to lawns in cottage areas), are impossible to evaluate quantitatively without a lake by lake survey.

With the above factors in mind, a reasonable phosphorus supply per capita-year can be calculated. According to the data of Bucksteeg (described in Vollenweider 1968), the annual per capita amount of phosphorus uptake in food in Germany in 1960 was 0.55 kg.; a similar amount is assumed to be excreted. In addition, the yearly per capita phosphorus supplied as domestic sewage (excrement + household wastes) in 13 studies in North America and Europe averaged 0.80 kg. $year^{-1}$, the studies having been carried out before use of high phosphate detergents was common. Thus, the two results are in basic agreement, and with food consumption in North America being greater than that in Europe and there being continued usage of high phosphate dishwashing detergents in North America, the higher figure of 0.80 kg phosphorus $capita^{-1}$ $year^{-1}$ is a good estimate of the phosphorus supplied from domestic sources.

For all lakes situated on the Precambrian Shield the artificial supply of phosphorus can therefore be calculated as:

$$J_A = \left(\frac{0.8 \text{ kg}}{\text{capita-year}} \times N \text{ cottages} \times T \frac{\text{capita-year}}{\text{cottage-year}}\right) \qquad (3)$$

where N = the number of cottages or dwelling units

T = the average number of capita years spent at each cottage in each year.

The same formula can be used for areas south of the Shield that consist

of sand, gravel or muck soils. For clay or clay-loam soils in the sedimentary area, a supply of 0.4 kg capita^{-1} year^{-1} which takes into account the retention capacity of the soil can be used.

The number of cottages or permanent dwellings (N) situated on a lake can be obtained by aerial photography (a good method is outlined in the Lake Alert Phase 2 report) or by field count. The time (in capita-years) spent at each dwelling per year (T) can be calculated using data gathered by the Department of Tourism and Information (1971). For cottages in the Haliburton region, 230 capita days per year, (or 0.63 capita-years per year), and in the Kawarthas, 253 capita days per year (or 0.69 capita-years per year) are spent at each cottage (based on a survey figure of 4.3 people per cottage). For permanent dwellings, the appropriate value for T is 1,570 capita-days per year (or 4.3 capita-years per year.) An actual field survey for a particular lake would undoubtably improve these figures; nevertheless, they will serve as adequate, generally applicable estimates.

In cases where holding tanks are employed and all wastes are removed to a treatment plant outside the lake's watershed, the supply of phosphorus from such dwellings should not be included in the calculations.

Recent investigations involving the use of an iron-clay fill around the tile bed have demonstrated a potential phosphorus removal mechanism. In cases where such modifications to conventional tile bed systems are used and known to be in working order, a per capita phosphorus supply figure of 0.16 kg is suggested (80% removal). A factor, $(1-R_s)$, can be included in the model to allow for alterations in the phosphorus removal capacity of the system.

The total supply to the lake can be calculated as the sum of the natural and artificial supplies;

$$
\begin{aligned}
J_T &= J_N + J_A \\
&= (\Sigma\ (A_d \cdot E_i) + L_{PR} \cdot A_o)/10^6 + 0.8\ \mathrm{N.T.}(1 - R_S) \qquad (4)
\end{aligned}
$$

where R_s is the retention capacity of the disposal system and will be equal to 0 for most Shield areas. The loading is, of course, equal to the supply per unit of lake area,

$$L_T = J_T/A_o.$$

Prediction of the Phosphorus Concentration in a Lake

1. Background

The description of the theory and derivation of nutrient budget models would be both voluminous and mathematically difficult for most readers of this manual; for those interested, a review of these models published to the end of 1972 has been prepared by Dillon (1974d). Additional work by Vollenweider (1973) and Imboden (1973, 1974) is also highly pertinent to the topic. The model used in this manual derived from Vollenweider (1969) is employed because a) it is simply derived and can be used with a minimum of field measurements and b) it alone has been tested for lakes in southern Ontario and has been found to have good predictive capabilities.

It can be assumed that the change in the concentration of phosphorus in a lake with time is equal to the supply added per unit volume minus the loss through sedimentation and the loss by outflow:

$$\frac{d\,[P]}{dt} = \frac{J}{V} - \sigma\,[P] - \rho\,[P] \qquad (5)$$

where [P] represents the phosphorus concentration (mg m^{-3}), J is the amount of phosphorus supplied per annum (mg yr^{-1}), V is the lake volume (m^3), σ is the sedimentation rate (yr^{-1}) and ρ is the flushing rate (yr^{-1}) which is equal to the total volume of water outflowing per year (Q) divided by the lake volume (V). Since the volume of the lake is equal to the surface area (A_o) times the mean depth ($\bar{z}$), equation (5) can be rewritten:

$$\frac{d\,[P]}{dt} = \frac{L}{\bar{z}} - (\sigma + \rho)\,[P] \qquad (6)$$

where $L = J/A_o$

The solution to this differential equation describing the concentration at a time t is:

$$[P] = \frac{L}{\bar{z}(\sigma+\rho)} \left[1 - \left(1 - \frac{\bar{z}(\sigma+\rho)\,[P]_0}{L}\right) e^{-(\sigma+\rho)t} \right] \qquad (7)$$

where $[P]_0$ is the initial concentration. The steady-state solution ($t \rightarrow \infty$) that we are interested in is simply:

$$[P] = \frac{L}{\bar{z}(\sigma+\rho)} \qquad (8)$$

2. Use of the Equation

Equation (8) can be used to predict the phosphorus concentration in a lake. The parameters required for this are the loading (L), mean depth ($\bar{z}$), sedimentation rate (σ) and flushing rate (ρ).

(a) Loading

Loading is calculated as described in the preceeding section.

(b) Mean Depth

Mean depth (as well as area and volume) for many lakes in Ontario can be obtained from the Ministry of Natural Resources Lake Inventory. If unavailable from this source, the lake will probably have to be echo-sounded, a contour map drawn, planimetered and the necessary morphometric parameters calculated. This is straightforward and is described in any standard limnological text (eg. Hutchinson 1957).

(c) Flushing Rate

The flushing rate (ρ) is calculated from the total outflow volume per year (Q) and the lake volume (V). Since this manual is

intended for use without fieldwork if possible, a method of calculation of Q is required. The long-term average annual areal runoff (r, in m yr^{-1}) has been mapped for Ontario south of the Shield by Coulson (1967) and for the entire Great Lakes Basin by Pentland (1968). Thus, virtually the entire area of recreational lakes in Ontario is mapped in terms of r, where r represents the differences between precipitation and evapotranspiration. The total long-term average inflow via surface runoff to a lake can therefore be calculated as $A_d \cdot r$. The total water balance can now be described by the equation:

$$Q = A_d \cdot r + A_o\ (Pr - Ev) \tag{9}$$

where $A_o \cdot Pr$ represents the direct input of water to the lake by precipitation and $-A_o \cdot Ev$ represents loss from the lakes by evaporation. The average value for Pr for a given area can be obtained from the Monthly Record or from isohyet maps (eg. Canada Land Inventory 1966) of Ontario. Maps of Ev (evaporation from lake surface) are given for Canada by Bruce and Weisman (1966). If A_d is large compared to A_o, then Q can be simply approximated as $A_d \cdot r$. In the few studies undertaken in Ontario (eg. Schultz 1950), groundwater has made a negligible contribution to the overal budget. The flushing rate, ρ, is then calculated as $Q(m^3\ yr^{-1})/V(m^3)$.

(d) Sedimentation Rate

Measurement of σ, the sedimentation rate coefficient, for phosphorus in a lake is, at best, extremely difficult. Fortunately, an alternate parameter, the retention coefficient, R, can be shown to have a functional relationship to σ. R is much more easily measured than σ; (R is equal to the fraction of the loading that is not lost via the outflow) as well, the retention coefficient has been shown to be predictable

(Kirchner and Dillon, unpublished studies).

The relationship derived between R and σ by Dillon and Rigler (1974a) under the same assumptions as employed in deriving the original model is:

$$\sigma = \frac{R\ \rho}{1-R}$$

Therefore, the equation (8) used to predict phosphorus concentration can be rewritten:

$$[P] = \frac{L\ (1-R)}{\bar{z}\ \rho}$$

Kirchner and Dillon (1974) determined by multiple regression analysis that R was highly correlated with Q/A_o, the areal water loading, usually written as q_s. Their prediction of R is:

$$R = 0.426 \exp(-0.271\ q_s) + 0.574 \exp(-0.00949\ q_s) \quad (12)$$

In some cases, the lake in question will have one or more lakes upstream which are sufficiently large to retain a significant amount of the total phosphorus exported from their respective portion of the watershed (see Figure 7). In the diagram the supply of phosphorus to Lake B is influenced by Lake A. This is taken into account by calculating the supply to Lake A, its retention coefficient (R_A), and multiplying J_A by ($1-R_A$) to give the fraction transferred to Lake B.

3. The Concept of Response Time of a Lake

As pointed out earlier change in the phosphorus loading to a lake results in a change in the phosphorus concentration and a subsequent change in water quality. The change is, of course, not instantaneous but

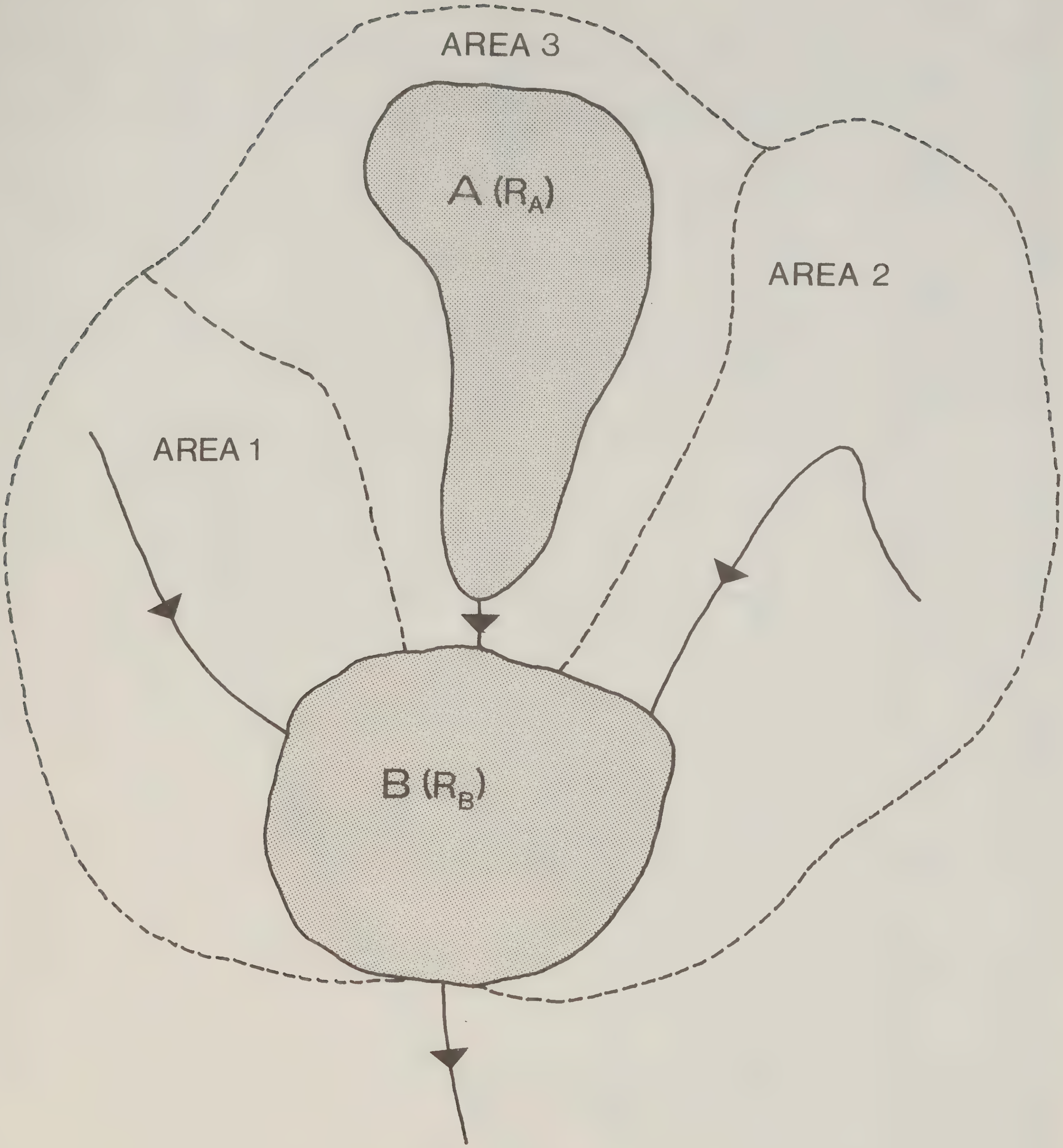

Figure 7: Calculation of the natural supply of phosphorus to Lake B from its drainage area. Lake A acts as a trap for nutrient exported from area 3. A_3 does not include the area of Lake A. Additional input to Lake B from precipitation and from artificial sources will be included in the final calculation of the supply.

$$J_B = E_1A_1 + E_2A_2 + (1-R_A)\ J_A$$

$$= E_1A_1 + E_2A_2 + E_3A_3\ (1-R_A)$$

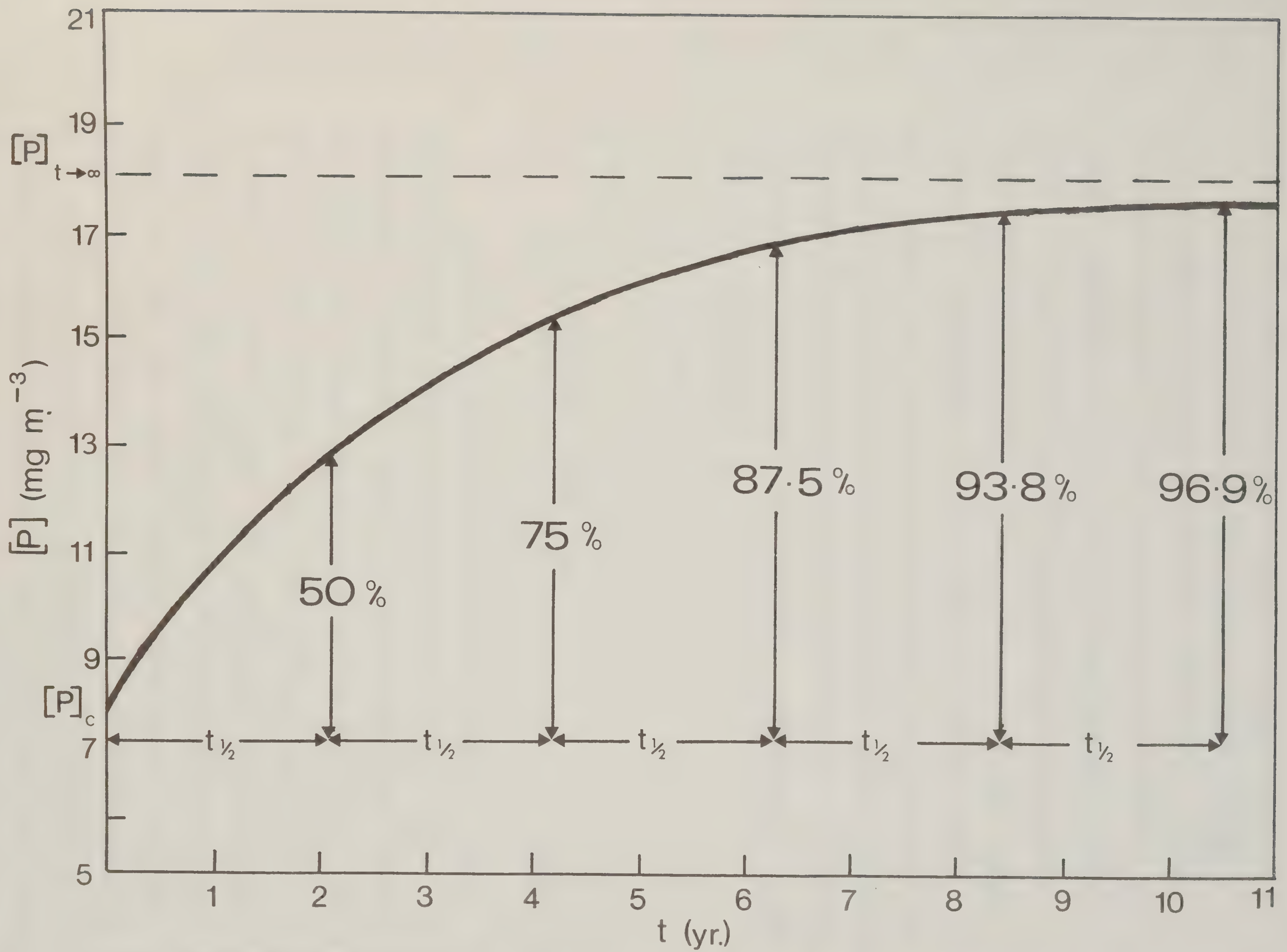

Figure 8: Phosphorus concentration as a function to time for a lake with an increase in loading. The initial concentration was 8 mg m^{-3}, the final steady state concentration is 18 mg m^{-3}, the half-life is 2.1 yr.

rather is described in equation (7) and shown in Figure 8.

The time required for a lake having an initial loading of L_1 to respond to a change in loading to a new level L_2, (L_2 can be greater or less than L_1) can be described by the half-life of the change in concentration, $t_{\frac{1}{2}}$ (ie. by the time required for the lake's phosphorus concentration to move half-way from the original steady-state concentration to the final steady-state concentration. Because equation (7) is exponential, two half-lives ($2t_{\frac{1}{2}}$) are required for the lake to reach 75% of its final concentration, $3 \cdot t_{\frac{1}{2}}$ for 87½%, etc. The half-life, $t_{\frac{1}{2}}$, depends only on the rate coefficients σ and ρ, representing the losses of phosphorus by sedimentation and outflow; it is independent of the loading level or the initial phosphorus concentration in the lake. It can be easily shown that

$$t_{\frac{1}{2}} = \ln 2/(\sigma+\rho)$$

or for our use:

$$t_{\frac{1}{2}} = \frac{(1-R)\ln 2}{\rho} = \frac{0.69\ (1-R)}{\rho} \qquad (13)$$

Therefore, one must consider the response time of a lake when predicting the effects of an increased loading (eg. resulting from development) or a decreased loading (eg. from improved sewage treatment facilities). It is suggested that 3 to 5 times the $t_{\frac{1}{2}}$ (ie. 87.5 - 96.9% of the way to the final steady-state concentration) be used as an indicator of the lake's response time. Characteristically, lakes with a rapid flushing rate will have short half-lives and therefore response times, while lakes that are very slowly flushed may take a long time to respond to a change in loading. For example, a lake with flushing rate of $\rho = 6\ yr^{-1}$ (ie. the lake's volume is replaced 6 times per year by flushing) and retention rate of R = 0.3 has a $t_{\frac{1}{2}}$ of 0.69 (.7)/6 = 0.08 yr. Therefore, between 0.24 and 0.40 years are required for the lake to approach a new steady-state following a change in loading.

Relationship of the Spring Phosphorus Concentration to the Summer Chlorophyll a Concentration and Water Transparency (Secchi Disc)

Based on the work of Sakamoto (1966), Dillon and Rigler (1974b) developed a predictive relationship suitable for estimating the average summer chlorophyll a concentration in lakes with spring N:P ratios > 12 (Figure 9). The data comprising this relationship were based on a combination of information presented by Sakamoto for 30 Japanese lakes, results for a wide variety of North American and European lakes reported by various authors, and information for 19 lakes in southern Ontario studied by Dillon and Rigler. The equation for the prediction of the summer average chlorophyll a concentration from the spring phosphorus concentration is:

$$\log_{10} [\text{chl } \underline{a}] = 1.45 \log_{10} [P] - 1.14 \qquad (14)$$

with [chl a] and [P] in mg m^{-3}

North temperate lakes typically have N:P ratios of 15 - 40.

The value of this relationship or "model" has been demonstrated in several cases. To date, the most comprehensive study of the effects of reduced nutrient load on a lake is that of Lake Washington (Edmondson 1969a). In 1952, ten sewage treatment plants discharged directly into the lake. Conditions in the lake (chlorophyll a concentration, Secchi disc depth, hypolimnetic oxygen deficit, phosphorus concentration, etc.) gradually deteriorated (detailed by Edmondson 1961, 1966, 1968, 1969b, 1972; Anderson 1960) until 1963, the year following initial steps to divert sewage. Diversion was completed by mid-1968, thereby reducing the phosphorus loading by 55%, at which point improvements were already noticed. Mean chlorophyll a concentration (July and August) which had been

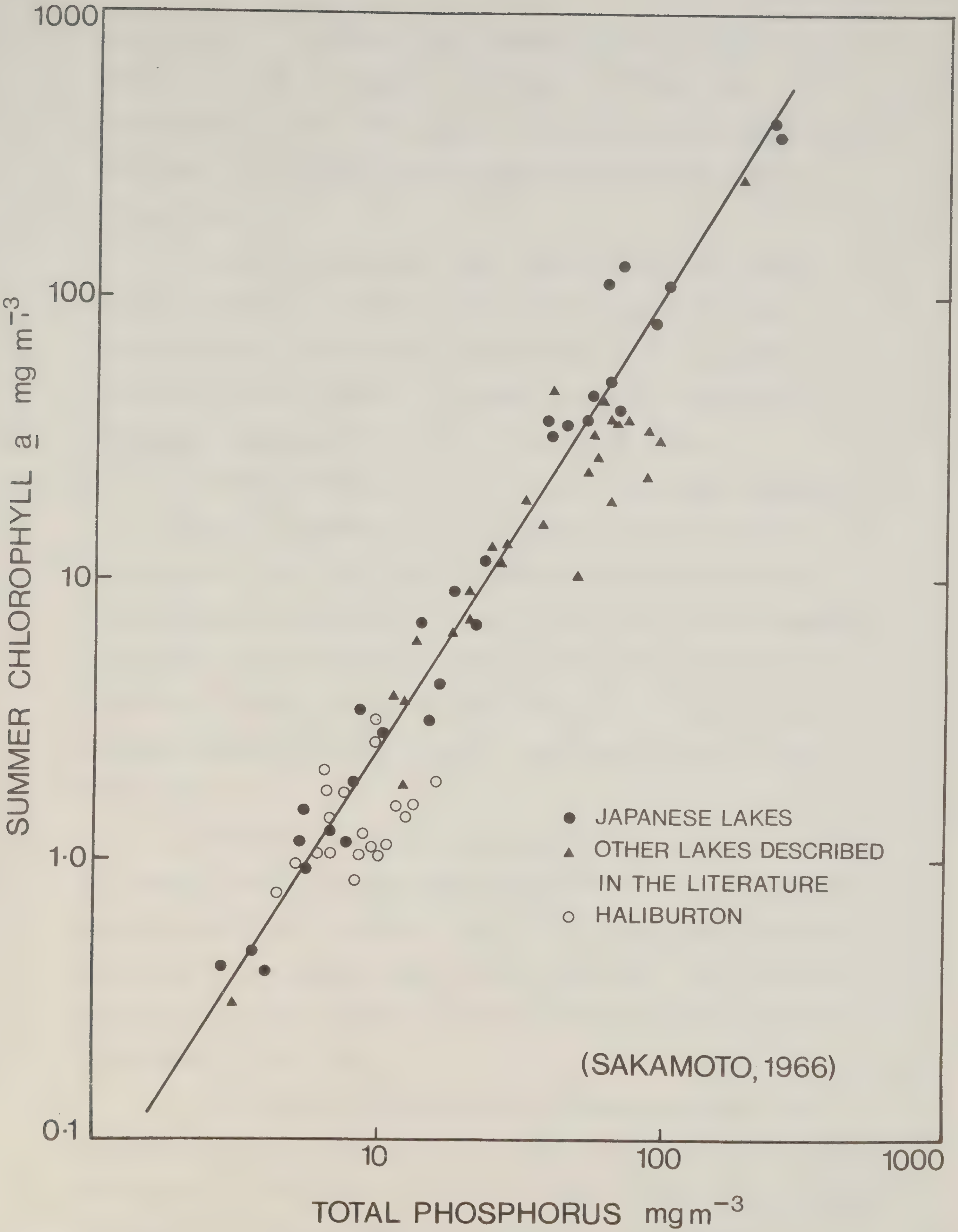

Figure 9: Relationship between average summer chlorophyll a concentration and spring total phosphorus concentration (from Dillon and Rigler 1974b).

about 1.5 mg m^{-3} in 1950 and had increased steadily to about 24 mg m^{-3} in 1964, was reduced to 3.5 mg m^{-3} in 1969. The important point is that the changes in phosphorus and chlorophyll a very closely parallelled those predicted by the Sakamoto plot (Figure 10).

In 1971, Little Otter Lake, a small Precambrian lake in Ontario, received a relatively large amount of a polyphosphate de-scaling agent (Michalski and Conroy 1973). The lake quickly developed classical symptons of eutrophy including a dense bloom of *Anabaena limnetica* G.M. Smith, low Secchi disc depths (0.1 - 2.3 m), and high chlorophyll a (12 - 46 mg m^{-3}) and total phosphorus (12 - 110 mg m^{-3}) concentrations. Polyphosphate discharges were discontinued in the fall of 1971; phosphorus concentration in the following spring dropped to 11.5 mg m^{-3}, which, according to equation (14) should have resulted in an average chlorophyll a concentration during the ice-free period of 1972 of 2.53 mg m^{-3}. The measured average concentration was 2.52 mg m^{-3}, an almost perfect fit (see Figure 10).

Additional phosphorus - chlorophyll a data have been supplied by Scheider and Rigler (unpublished studies) for 6 lakes in Algonquin Park, by Oglesby and Shafner for some of the Finger Lakes in New York State, and by Bachman and Jones for some Iowa lakes. These data are also shown in Figure 10 and it is apparent that in all cases the fit to the model is very good.

It is expected that chlorophyll a concentration will be inversely related to the Secchi disc reading, (a measure of the water's transparency). Collection of data for a large number of lakes is shown in Figure 11. From the predicted chlorophyll a concentration, a prediction of the likely average Secchi disc reading is possible. Care

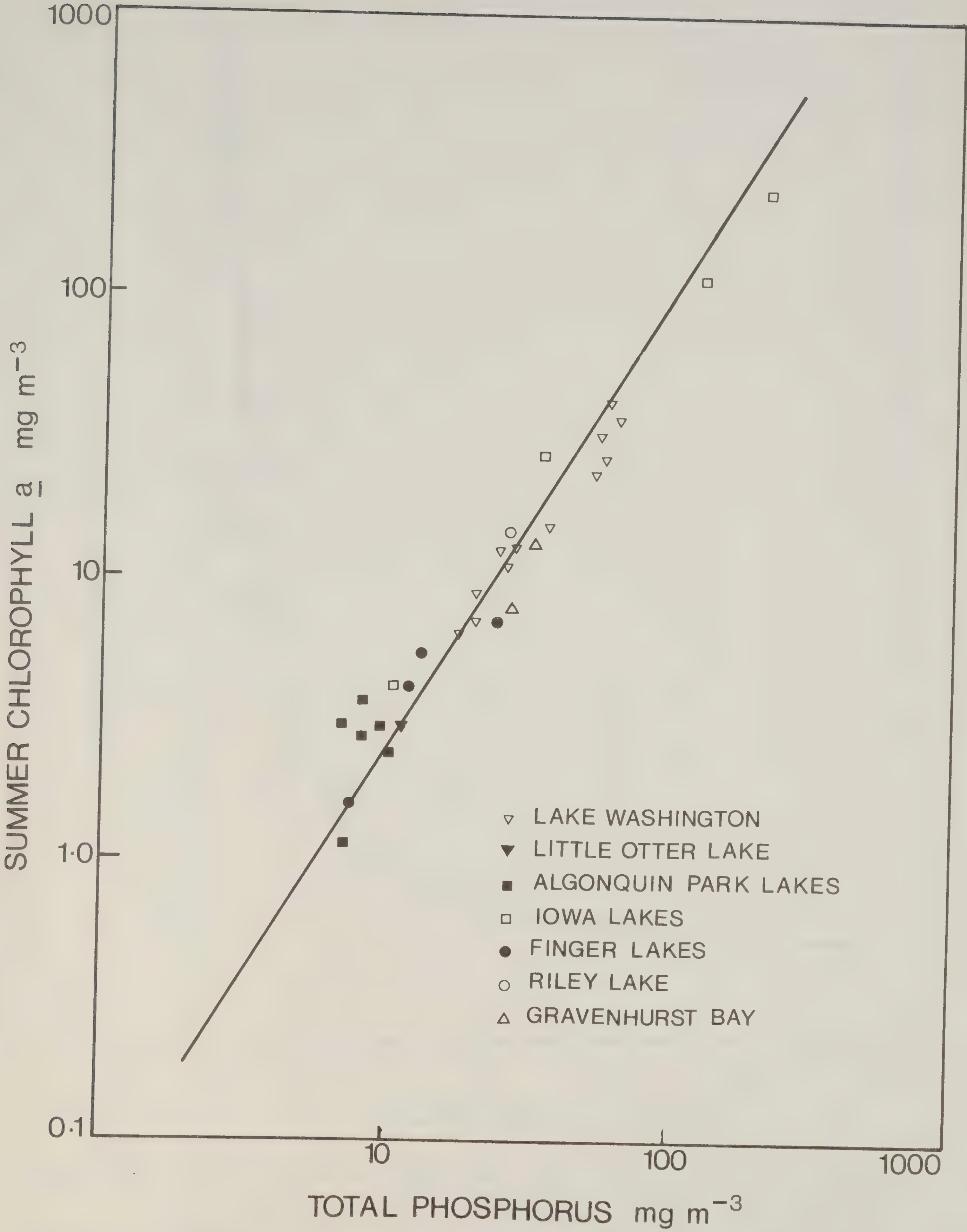

Figure 10: Additional spring phosphorus - summer chlorophyll data with line as derived from data shown in Figure 9.

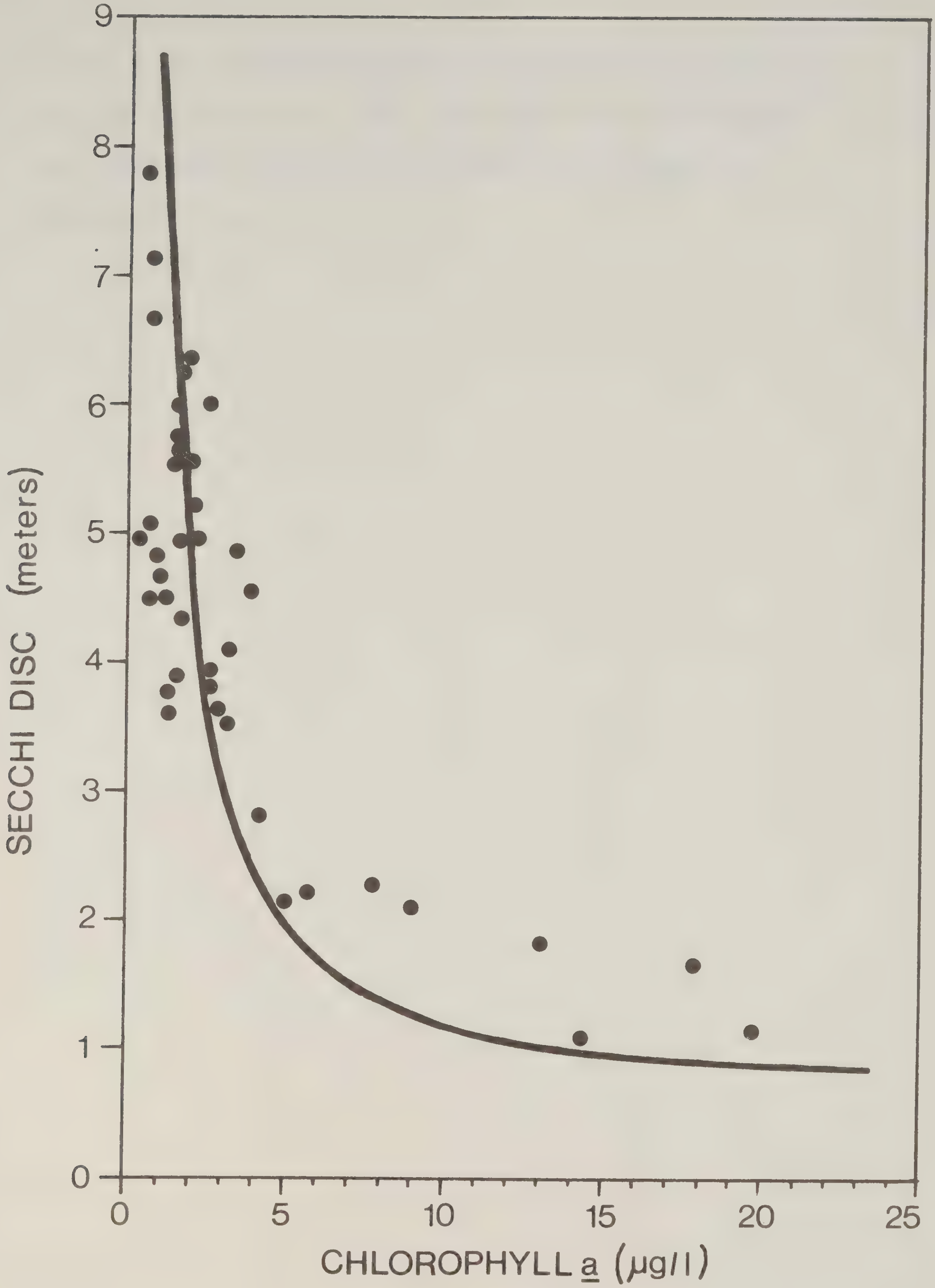

Figure 11: The relationship between Secchi disc and chlorophyll a for thirty-five lakes in the Haliburton Highlands region of Ontario. Values for each lake are based on means of values collected during the summer of 1973. Also, information from a number of other lakes is included as an indication of the relative status of lakes in the study area.

must be taken in interpreting this relationship in the case of dystrophic (brown water) lakes, whose Secchi disc readings are lower than would be expected on the basis of chlorophyll a concentration alone.

Potential Fish Yield

Ryder's (1965) morphoedaphic index (MEI), TDS/$\bar{z}$ (total dissolved solids divided by mean depth) provides the best method of estimating the potential fish yield of the lake in question. The concentration of total dissolved solids in a lake fluctuates little over the year, so the time of measurement is not critical. The equation used to predict yield is:

$$F = 1.10\ (TDS/\bar{z})^{0.446} \tag{15}$$

where F is the fish yield in kg/ha, TDS is measured in ppm and $\bar{z}$ in meters.

The limitations of this model should be stressed. Although an estimate of the potential sustainable fish yield is given, the effects of development on the fishery is unspecified. Over-development leading to excess nutrient input followed by a winter "fish kill" due to oxygen depletion under the ice or followed by greatly increased fish growths rates obviously results in a change in the fishery, but there is not necessarily a change in the MEI that would lead to prediction of either case.

STEPWISE PROCEDURE FOR CALCULATING THE DEVELOPMENT CAPACITY OF A LAKE

STEP 1. Based on long-range plans for the lake, decide what the maximum permissible average summer chlorophyll a concentration will be:

Level 1: 2 mg m^{-3}; for lakes to be used primarily for body contact water recreation, and where it is desirable to maintain hypolimnetic concentrations of oxygen in excess of 5 mg l^{-1}. The lake will be extremely clear with a mean Secchi disc visibility of >5 m and will be very unproductive. (Note - The Secchi disc visibility may be lower in brown water (dystrophic) lakes).

Level 2: 5 mg m^{-3}; for lakes to be used for water recreation but where the preservation of cold water fisheries is not imperative. The lake will be moderately productive and correspondingly less clear, with a mean Secchi disc visibility of 2 - 5 m.

Level 3: 10 mg m^{-3}; for lakes where body-contact recreation is of little importance, but emphasis is placed on fisheries (bass, walleye, pickerel, pike, maskinonge, bluegill, yellow perch). Hypolimnetic oxygen depletion will be a common occurrence. Secchi disc depths will be low (1-2 m), and there is a danger of winterkill of fish in shallow lakes.

Level 4: 25 mg m^{-3}; suitable only for warm water fisheries. Secchi disc depth <1.5 m, hypolimnetic oxygen depletion beginning early in summer, considerable danger of winterkill of fish except in deep lakes.

The planning agency may pick any intermediate level should it so desire.

STEP 2. From the chosen summer average chlorophyll a concentration, calculate the permissible spring phosphorus concentration, [P] from:

$$\log_{10} [\text{chl } \underline{a}] = 1.45 \log_{10} [P] - 1.14$$

$$\text{ie. } \log_{10} [P] = \frac{\log_{10} [\text{chl } \underline{a}] + 1.14}{1.45}$$

eg.

[chl a]	[P]
2 mg m^{-3}	9.9 mg m^{-3}
5	18.5
10	29.9
25	56.3

STEP 3. Determine the lake surface area (A_o in m^2), mean depth ($\bar{z}$ in m) and volume (V in m^3) from the Ministry of Natural Resources Lake Inventory (multiply acre-feet by 1233.6 to get m^3). If such data are not available, the lake must be properly sounded (preferably with an echo-sounder) and a contour map drawn. The area (A_o) is obtained by planimetry from an aerial photo of known scale.

STEP 4. Outline the lake's drainage area on a 1:50,000 scale topographic map and calculate the area (A_d in m^2) by planimetry (example shown in Figure 12). The following guidelines may help delineate the drainage basin boundary:

1) boundaries are generally drawn by following the high points of land
2) assume that water flows downhill to the nearest contour line
3) assume that groundwater follows the drainage pattern of surface water.

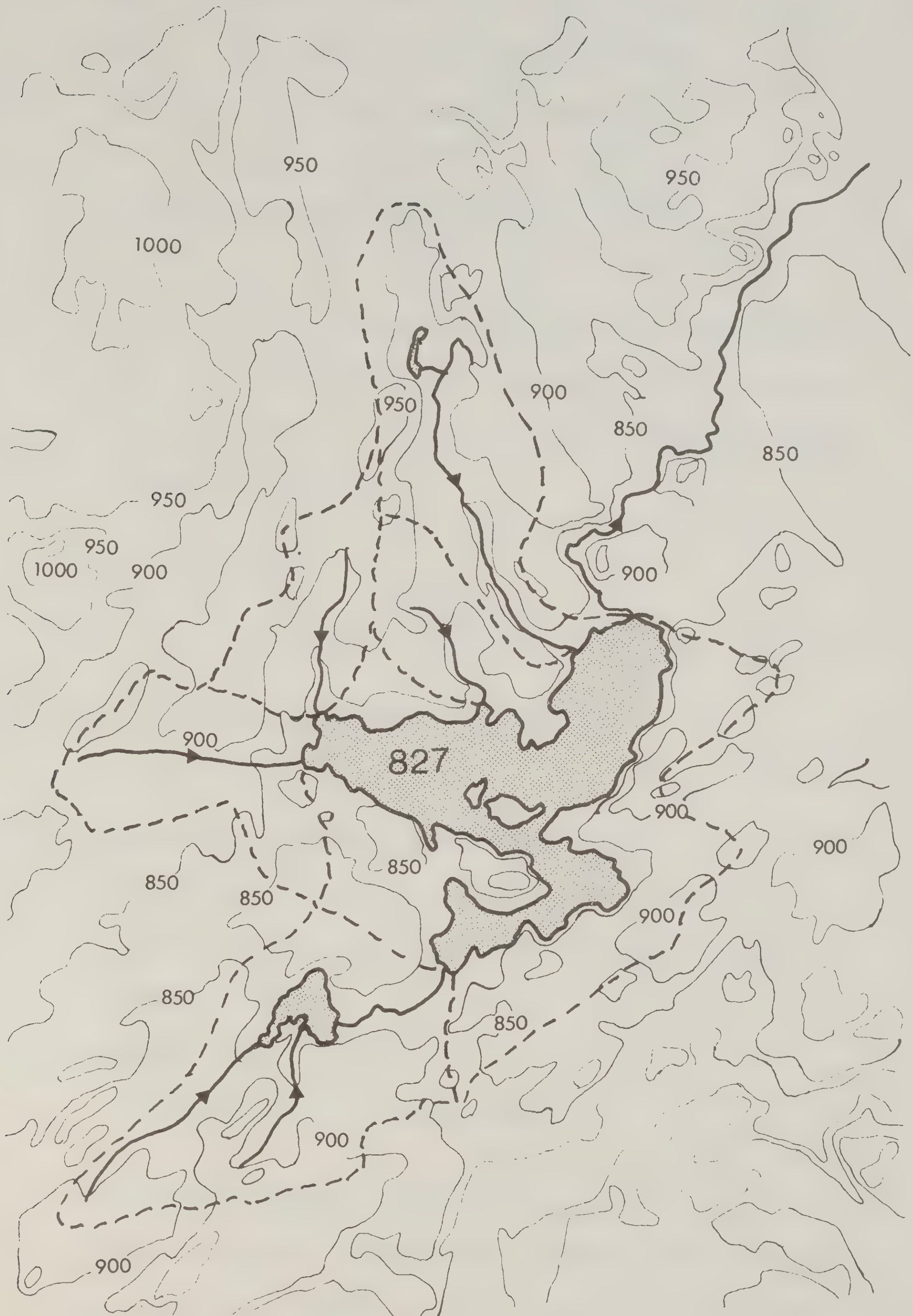

Figure 12: Example of a lake's drainage area outlined from a topographic map.

STEP 5. From Figure 13 taken from Pentland (1968) determine the total amount unit runoff (r) in cfs mi^{-2} and convert to $m^3\ yr^{-1}\ m^{-2}$ or $m\ yr^{-1}$ by multiplying by 0.345.

STEP 6. Calculate Q, the total outflow volume as:

$$A_d \cdot r \quad (m^3\ yr^{-1})$$

and calculate the flushing rate (ρ) as Q/V or

$$(A_d \cdot r)/V \quad (yr^{-1})$$

If A_d is < 10 A_o, determine the mean annual precipitation (Pr) from Figure 14 and the mean annual lake evaporation (Ev) from Figure 15, convert to $m\ yr^{-1}$ by multiplying by 0.0254 and calculate Q:

$$Q = A_d \cdot r + A_o\ (Pr\text{-}Ev)$$

$$\therefore \quad \rho = \frac{A_d \cdot r + A_o\ (Pr\text{-}Ev)}{V} \qquad (yr^{-1})$$

STEP 7. Calculate the areal water load (q_s) as

$$Q/A_o \qquad (m\ yr^{-1})$$

STEP 8. Calculate the retention coefficient (R) as

$$R = 0.426 \exp(-0.271\ q_s) + 0.574 \exp(-0.00949\ q_s)$$

STEP 9. Calculate the response time of the lake to a change in phosphorus loading:

$$\text{Response time} = (3 \rightarrow 5)\ t_{\frac{1}{2}}$$

$$= (3 \rightarrow 5)\ \frac{(1-R)\ \ln 2}{\rho} \qquad (yr)$$

This will provide an indication of the time required for a lake to "respond" to development and will give an idea of when follow-up studies (if any) should be carried out. Conversely, the response time can assist in the interpretation of present water quality. For example, a lake with 250 new cottages may appear to be in good condition, but, if one can calculate that it has a response time of 6 - 10 years,

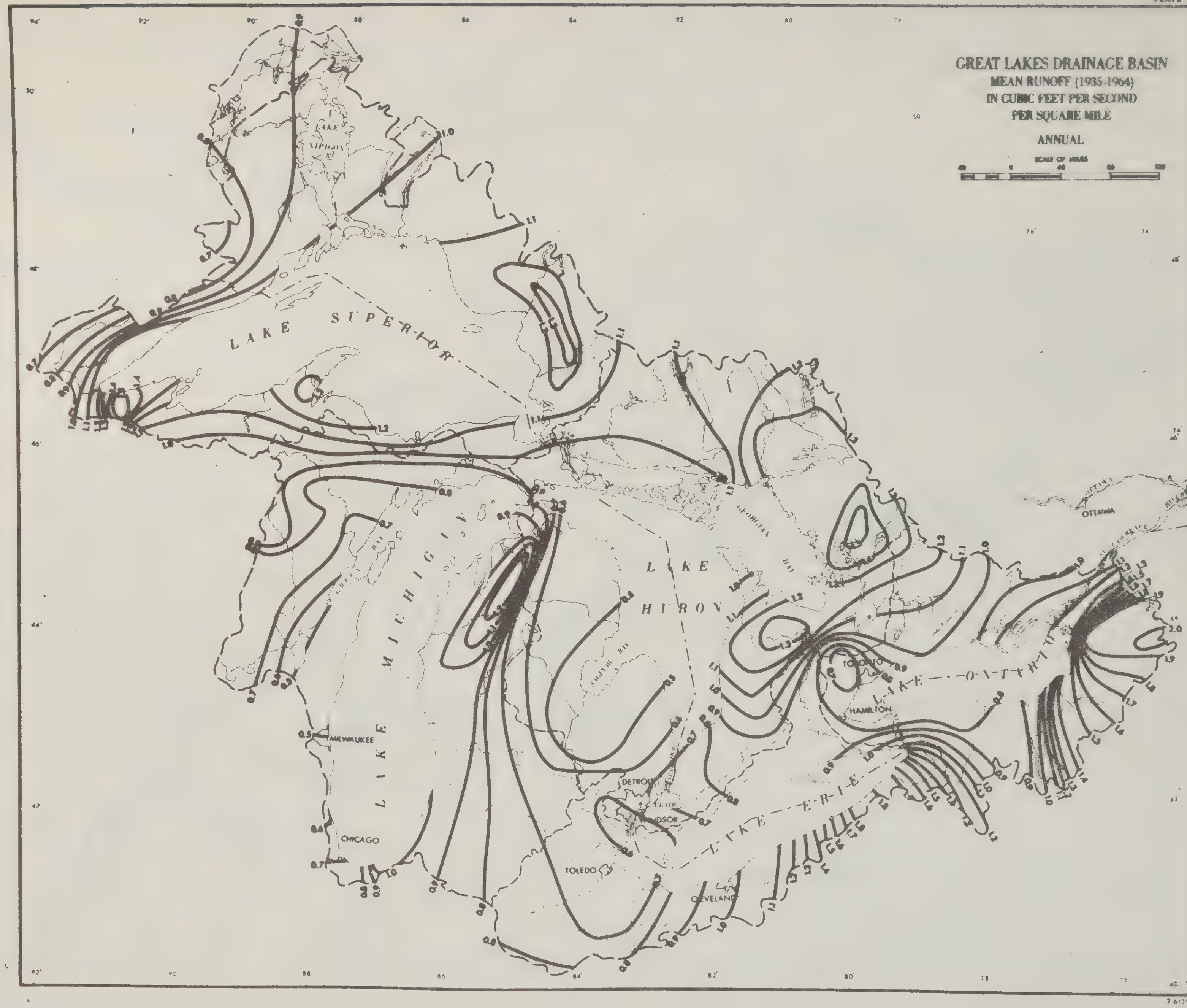

Figure 13: Average annual areal runoff (from Pentland 1968).

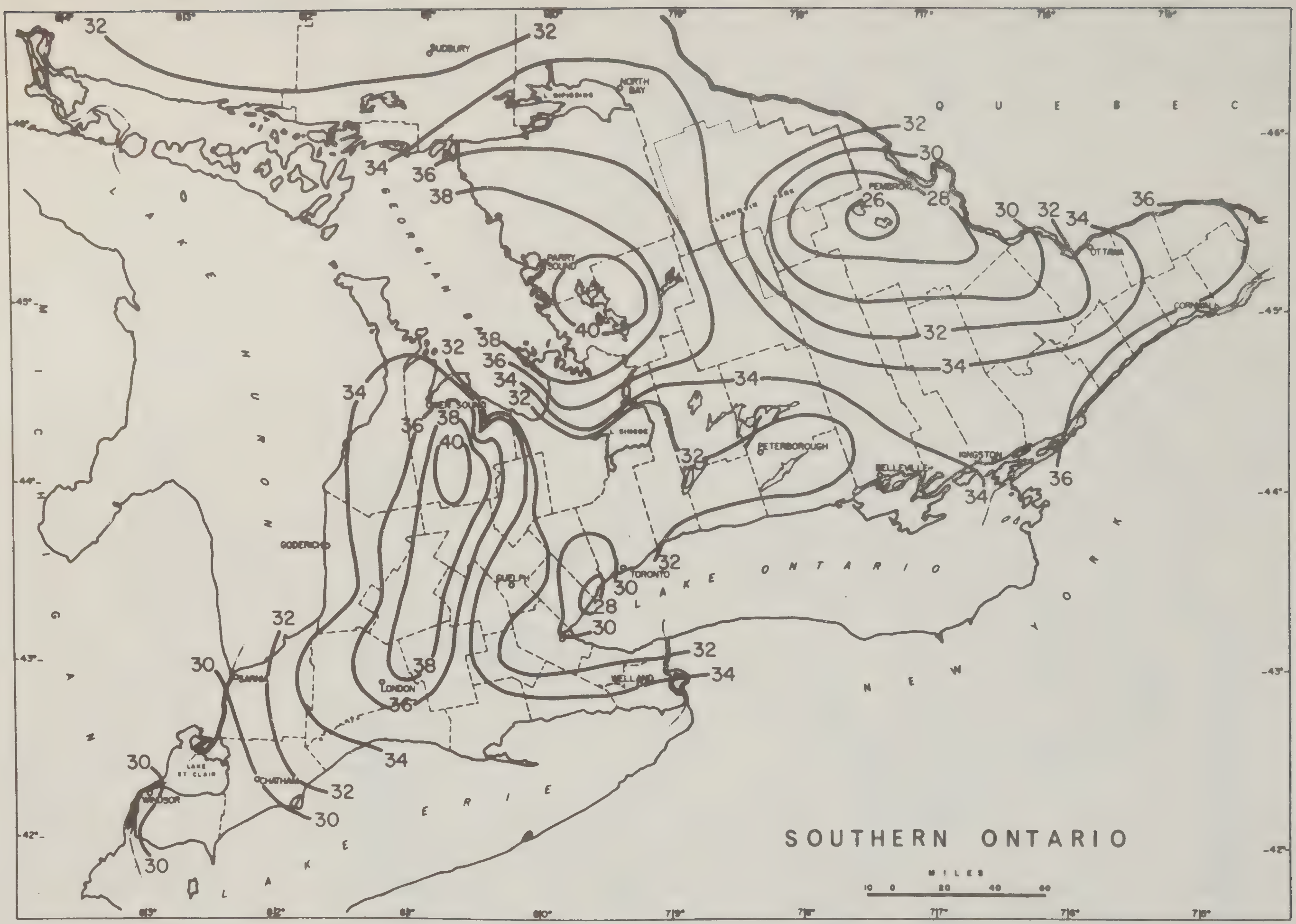

Figure 14a: Mean annual precipitation - Southern Ontario.

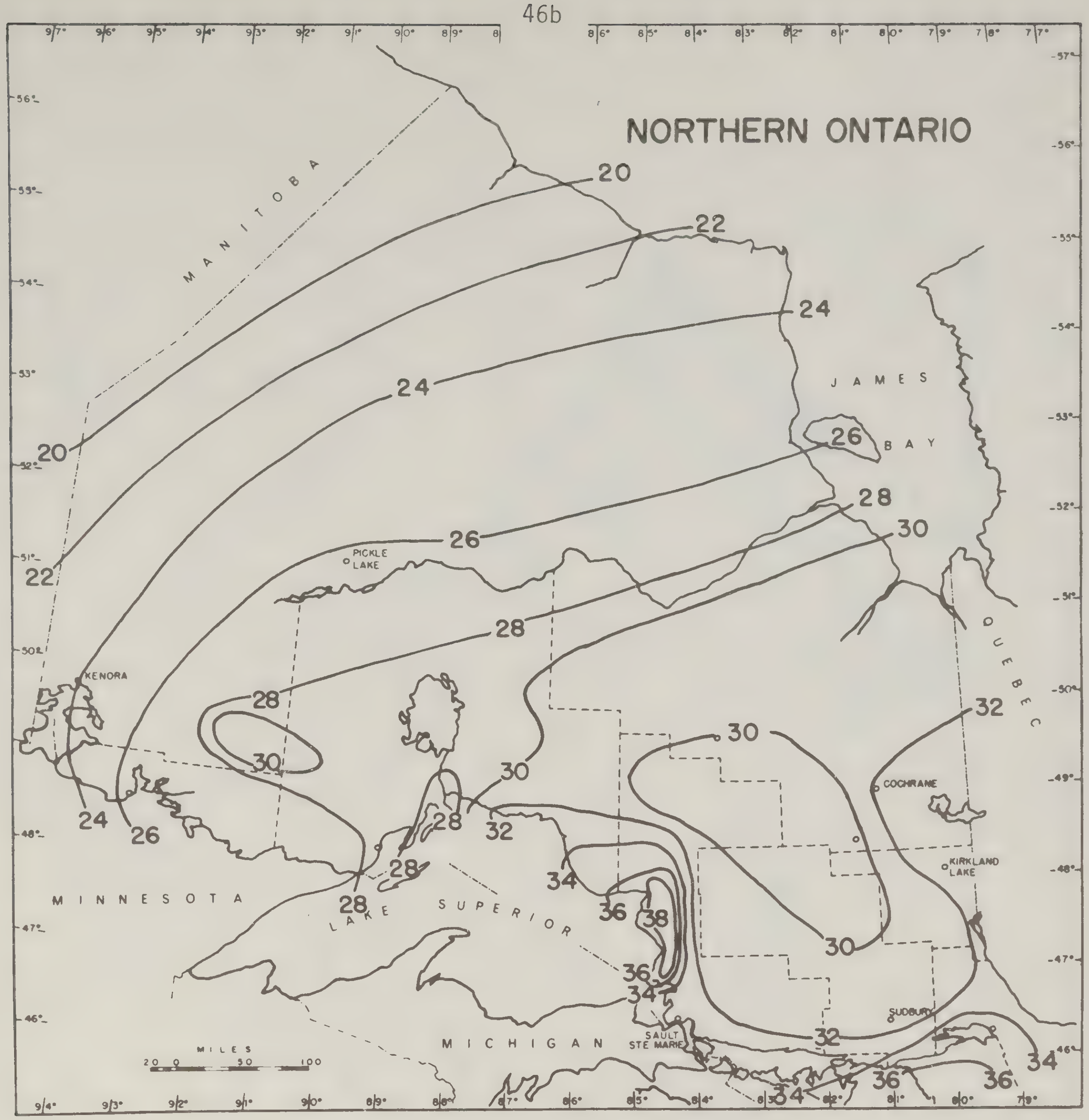

Figure 14b: Mean annual precipitation - Northern Ontario.

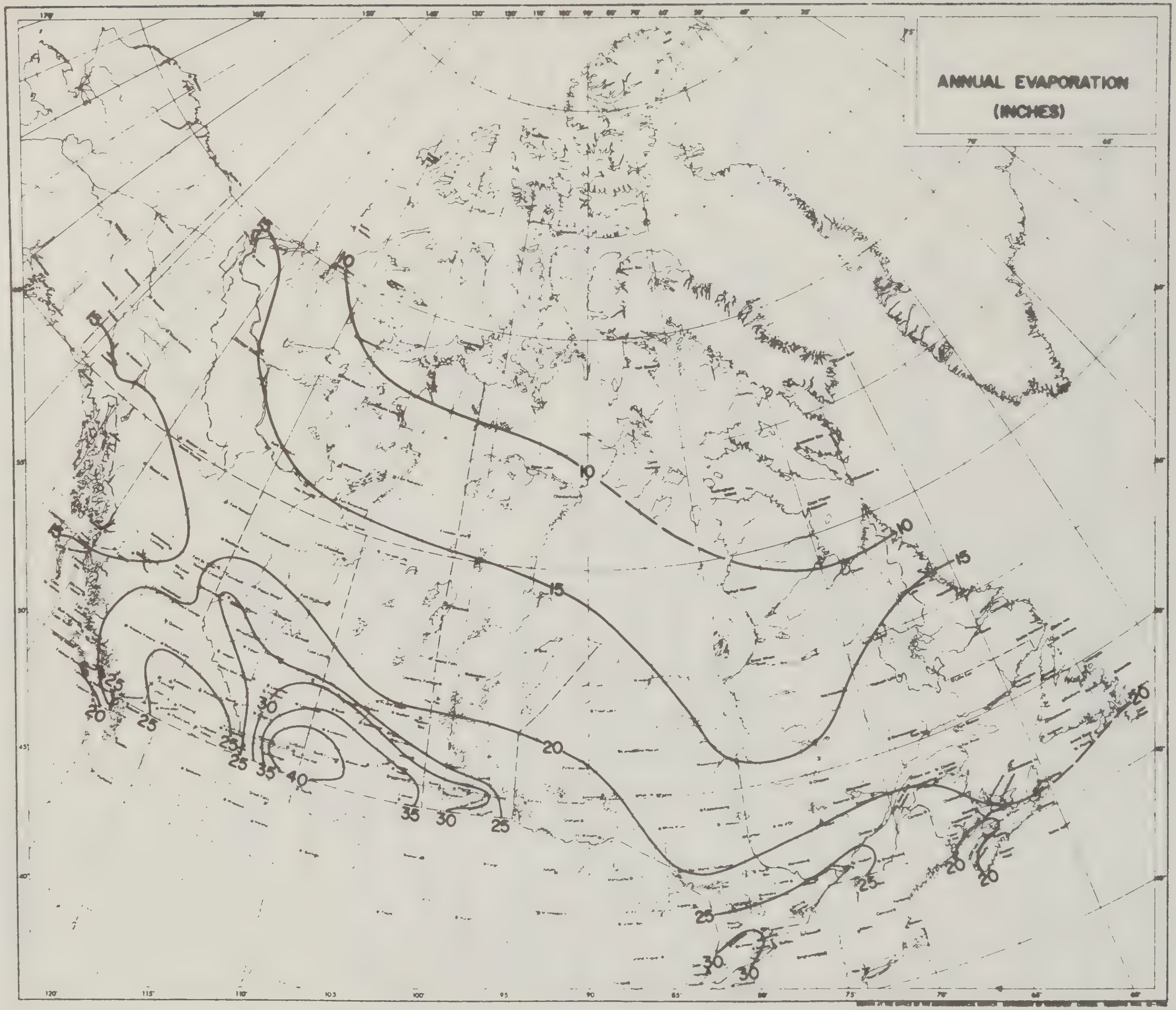

Figure 15: Mean annual lake evaporation (from Bruce and Weisman 1966).

then caution is necessary before additional development is allowed.

STEP 10. Calculate the permissible phosphorus load (L_{perm}) to the lake:

$$L_{perm} = \frac{[P] \cdot \bar{z} \cdot \rho}{(1-R)} \qquad (mg\ m^{-2}\ yr^{-1})$$

and the permissible supply (J_{perm})

$$J_{perm} = \frac{L_{perm} \cdot A_o}{10^6} \qquad (kg\ yr^{-1})$$

STEP 11. Divide the watershed of the lake (on the topographic map) into subunits for all inflows and determine the area for each one (A_{di}). From the most recent aerial photos available determine if > 15% of the area of each watershed is either cleared land or marsh. Determine whether the watershed (not just the lake) is on Precambrian igneous rock or on sedimentary rock, and estimate the export (E $mg\ m^{-2}\ yr^{-1}$) for each subwatershed from Table 1. Calculate the total supply of phosphorus from the land to the lake:

$$J_E = (\sum_i A_{di} \cdot E)/10^6 \qquad (kg\ yr^{-1})$$

and the load

$$L_E = (\sum_i A_{di} \cdot E)/A_o \qquad (mg\ m^{-2}\ yr^{-1})$$

Take consideration of an upstream lake by reducing the supply to the downstream lake from the subwatershed containing the upstream lake by multiplying by $(1-R^1)$ where R^1 is the phosphorus retention coefficient of the upstream lake. R^1 is calculated as in Step 8, using q_s for the upstream lake.

STEP 12. The phosphorus load from precipitation, L_{PR}, is 75 $mg\ m^{-2}\ yr^{-1}$. Calculate the supply from precipitation as:

$$J_{PR} = \frac{75 \cdot A_o}{10^6} \qquad (\text{kg yr}^{-1})$$

STEP 13. The natural supply and natural loading are:

$$J_N = J_E + J_{PR}$$

$$L_N = L_E + L_{PR}$$

If $J_N > J_{perm}$, ie. if the natural supply is greater than the permissible supply, allow no (further) development.

STEP 14. Determine the present number of cottages (N_C) and permanent dwellings (N_D) within 300 m (1000 ft.) of the lake or any of the inflowing streams or rivers from recent aerial photographs or field surveys. For cottages, assume 253 capita-days per year (0.69 capita-years yr^{-1}) in the Kawarthas, 230 capita-days per year (0.63 capita-years yr^{-1}) elsewhere. Assume 4.3 people per dwelling, and calculate N_{CY} the number of capita-years yr^{-1} spent at the lake:

$$N_{CY} = 0.63 \times N_C + 4.3 \times N_D$$

(0.69 replaces 0.63 in the Kawarthas)

ie. one permanent unit = 6.8 cottage units (6.2 in Kawarthas)

STEP 15. Calculate the phosphorus supplied to the lake from the cottage units (artificial supply) as:

$$J_A = 0.8 \times N_{CY} (1-R_s) \qquad (\text{kg yr}^{-1})$$

where R_s = 0 for conventional septic tank - tile field systems on the Precambrian Shield. If there is firm evidence that holding tanks are used for all household wastes and the systems are pumped and removed to a treatment plant outside of the watershed, neglect such cottage(s) in the calculations. If

there is firm evidence of properly functioning iron-clay tile beds, use a figure of 0.16 kg/capita-year instead of 0.8 kg/capita-year ($R_s = 0.8$) for the appropriate locations. The artificial load (L_A) is

$$\frac{J_A \times 10^6}{A_o} \qquad (\text{mg m}^{-2}\ \text{yr}^{-1})$$

STEP 16. Calculate the present total supply of phosphorus to the lake:

$$J_T = J_N + J_A \qquad (\text{kg yr}^{-1})$$

If $J_T \geq J_{perm}$, allow no further development.

STEP 17. If $J_T < J_{perm}$, calculate the total permissable number of cottage units:

$$N_{perm} = \frac{J_{perm} - J_N}{0.63 \times 0.8} \qquad \frac{\text{kg/yr}}{\frac{\text{capita yr}}{\text{cottage yr}} \cdot \frac{\text{kg}}{\text{capita yr}}}$$

STEP 18. The additional number of cottage units permitted is:

$$N_{ADD} = N_{perm} - N_{CY}$$

STEP 19. Check to be sure that N_{perm} does not exceed that BOAT/LIMIT figure given by the Lake Alert method.

STEP 20. With the aid of personnel of the Ministry of Natural Resources, locate the cottage units to avoid damage to spawning grounds, wildlife habitat, etc. With the assistance of personnel of the Ministry of the Environment, locate the septic tile beds in the most suitable locations. (the points mentioned above may, at the planners discretion, serve as constraints reducing the permissible number of cottage units below N_{CY}).

EXAMPLES

EXAMPLE A. To determine the development capacity of SKELETON LAKE, MUSKOKA.

STEP

1. Skeleton Lake is ideal for a cold water fishery and body contact recreation and should be kept at Level 1 if possible. Therefore:

$$[\text{chl } \underline{a}] = 2 \text{ mg m}^{-3}$$

2. Permissible [P] = 9.9 mg m^{-3}

3. $A_o = 20 \times 10^6 \text{ m}^2$

   $\bar{z} = 30.0 \text{ m}$

   $V = 600 \times 10^6 \text{ m}^3$

4. $A_d = 58 \times 10^6 \text{ m}^2$

5. $r = 1.45 \text{ cfs/mi}^2 = 0.500 \text{ m yr}^{-1}$

6. Since $A_d < 10\, A_o$, determine

$$Pr = 38'' = 0.965 \text{ m}$$

$$Ev = 24'' = 0.610 \text{ m}$$

$$\therefore Q = 58 \times 10^6 \times 0.500 + (20 \times 10^6)(0.355) = 36.1 \times 10^6 \text{ m}^3\text{yr}^{-1}$$

$$\rho = \frac{29 \times 10^6 + (20 \times 10^6)(0.355) \text{ yr}^{-1}}{600 \times 10^6} = 0.06 \text{ yr}^{-1}$$

7. $q_s = \frac{Q}{A_o} \text{ m yr}^{-1} = \frac{36.1 \times 10^6}{20 \times 10^6} = 1.81 \text{ m yr}^{-1}$

8. $R = 0.426 \exp(-0.271 \times 1.81) + 0.574 \exp(-0.00949 \times 1.81)$

   $= 0.83$

9. Response time

$$= (3 \div 5)\ \frac{(0.17)(0.69)}{0.060}$$

$$= 5.9 - 9.8 \text{ yr}$$

10. $L_{perm} = \frac{9.9 \times 30 \times 0.06}{0.17}$

$$= 105 \text{ mg m}^{-2}\text{yr}^{-1}$$

$$J_{perm} = \frac{105 \times 20 \times 10^6}{10^6}$$

$$= 2100 \text{ kg yr}^{-1}$$

11. All of Skeleton Lake's watershed is of one geology and land use - forested igneous.

$\therefore$ $E = 4.7$ mg $m^{-2}yr^{-1}$

$\therefore$ $J_E = 4.7 \times 58 \times 10^6$ mg yr^{-1}

$= 273$ kg yr^{-1}

12. $$J_{PR} = \frac{75 \times 20 \times 10^6}{10^6} \text{ kg yr}^{-1}$$

$$= 1500 \text{ kg yr}^{-1}$$

13. $J_N = 273 + 1500$ kg yr^{-1}

$= 1773$ kg P yr^{-1}

$\therefore$ $J_N < J_{perm}$

14. $N_c = 370$ cottages

$N_D = 0$

$\therefore N_{cu} = 370$ cottage units

15. $J_A = 0.8 \times 370 \times 0.63$ kg P yr^{-1}

$= 186.5$kg P yr^{-1}

16. $J_T = 1773 + 186.5$ kg ρ yr^{-1}

$= 1960$ kg P yr^{-1}

$J_T < J_{perm}$

17. $$N_{perm} = \frac{2100 - 1773}{0.63 \times 0.8} \text{ cottage units}$$

$= 649$ cottage units

18. The additional number of cottage units allowed is:

$N_{ADD} = 649 - 370$

$= 279$ cottage units

ie. 279 cottages or 41 permanent dwellings

ALTERNATE CALCULATION

1. If it were decided to allow Skeleton Lake to deteriorate to Level 2 then the following calculations apply:

2. $[P] = 18.5 \text{ mg m}^{-3}$

3.-9. as before

10. $L_{perm} = \dfrac{18.5 \times 30 \times 0.060}{0.17} = 196 \text{ mg m}^{-2}\text{yr}^{-1}$

$J_{perm} = 3918 \text{ kg yr}^{-1}$

11. $J_E = 273 \text{ kg yr}^{-1}$

12. $J_{PR} = 1500 \text{ kg yr}^{-1}$

13. $J_N = 1773 \text{ kg yr}^{-1}$

14. $N_{cu} = 370$ cottage units

15. $J_A = 186.5 \text{ kg yr}^{-1}$

16. $J_T = 1960 \text{ kg yr}^{-1}$

17. $N_{perm} = \dfrac{3918 - 1773}{0.63 \times 0.8}$

$= 4260$ cottage units

18. $N_{ADD} = 3890$ cottage units

$= 3890$ cottages or 570 permanent dwellings

ie. a small town would be permissible

EXAMPLE B. To determine the effect of a development of 250 cottages on the water quality of BOB LAKE, HALIBURTON.

STEP

3. $A_o = 2.27 \times 10^6\ m^2$

$\bar{z} = 18.0\ m$

$V = 40.7 \times 10^6\ m^3$

4. $A_d = 29.0 \times 10^6\ m^2$

5. $r = 1.25\ cfs/mi^2 = 0.431\ m\ yr^{-1}$

6. $Q = 29.0 \times 10^6 \times 0.431$

$= 12.5 \times 10^6\ m^3 yr^{-1}$ $(A_d > 10\ A_o)$

$\rho = 0.31\ yr^{-1}$

7. $q_s = \dfrac{12.5 \times 10^6}{2.27 \times 10^6} = 5.51\ m\ yr^{-1}$

8. $R = 0.64$

9. $t_{\frac{1}{2}} = \dfrac{0.36 \times \ln 2}{0.31} = 0.8\ yr$

Response time = 2.4 - 4.0 yr

11. $J_E = \dfrac{4.7 \times 29 \times 10^6}{10^6}$ kg P yr^{-1}

$= 136.3$ kg P yr^{-1}

12. $J_{PR} = \dfrac{75 \times 2.27 \times 10^6}{10^6}$

$= 170.3$ kg P yr^{-1}

13. $J_N = 136.3 + 170.3$

$= 307$ kg P yr^{-1}

L_N = 135 mg m^{-2} yr^{-1}

14. At present

N_C = 25 cottages

N_D = 3 permanent dwellings

$\therefore N_{CU} = 25 + \frac{3 \times 4.3}{0.63}$

= 45.5 cottage units

15. J_A = 0.8 X 45.5 X 0.63

= 22.9 Kg P yr^{-1}

16. J_T = 330 kg P yr^{-1}

L_T = 145 mg P m^{-2} yr^{-1}

$\therefore$ The <u>predicted</u> spring phosphorus concentration at present is:

$$[P] = \frac{L(1-R)}{\bar{z}\,\rho}$$

$$= \frac{145\ (0.36)}{18.0\ (0.31)}$$

$$= 9.4 \text{ mg m}^{-3}$$

The <u>measured</u> spring total phosphorus concentration (1972) was 8.5 mg m^{-3}, very close.

<u>Predicted</u> summer average chlorophyll <u>a</u> concentration is: 1.87 mg m^{-3} (Level 1) cf. <u>measured</u> 1.23 mg m^{-3}

Effects of a development of 250 cottages:

14. N_{CU} = 45.5 + 250

= 295.5 cottage units

15. J_A = 0.8 X 285.5 X 0.63

149 kg P yr^{-1}

16. J_T = 307 + 149 = 456 kg P yr^{-1}

$L_T = 201 \text{ mg m}^{-2} \text{ yr}^{-1}$

$\therefore$ The predicted spring phosphorus concentration at the new steady-state level is:

$$[P] = \frac{201\ (0.36)}{18.0\ (0.31)}$$

$$= 13.0 \text{ mg m}^{-3}$$

The predicted summer average chlorophyll *a* concentration is: 3.0 mg m^{-3} (Level 2). The Secchi disc readings would average about 3 m compared to the present 5 -7 m (see Figure 11).

EXAMPLE C. To determine the development capacity of MISKWABI LAKE, HALIBURTON.

STEP

1. Miskwabi Lake is a deep lake of high water quality and should not be developed beyond Level 1.

   $\therefore$ [chl *a*] $= 2 \text{ mg m}^{-3}$

2. Permissible [P] $= 9.9 \text{ mg m}^{-3}$

3. $A_o = 2.68 \times 10^6 \text{ m}^2$

   $\bar{z} = 19.1 \text{ m}$

   $V = 51.5 \times 10^6 \text{ m}^3$

4. $A_d = 10.5 \times 10^6 \text{ m}^2$

5. $r = 1.22 \text{ cfs/mi}^2 = 0.421 \text{ m yr}^{-1}$

6. $A_d < 10\ A_o$

   $\therefore\ Q = 10.5 \times 10^6 \times 0.421 + 2.68\ (0.838 - 0.610) \times 10^6$

   $= 5.03 \times 10^6 \text{ m}^3$

   $$\rho = \frac{5.03 \times 10^6}{51.5 \times 10^6} = 0.098 \text{ yr}^{-1}$$

7. $q_s = \dfrac{5.03 \times 10^6}{2.68 \times 10^6} = + 1.88 \text{ m yr}^{-1}$

8. R = 0.82

9. $t_{1/2} = \dfrac{(0.18) \ln 2}{0.098}$

$= 1.27$

Response time = 3.8 - 6.3 yr

10. $L_{PERM} = \dfrac{9.9 \times 19.1 \times 0.098}{0.18}$

$= 103 \text{ mg m}^{-2} \text{ yr}^{-1}$

$J_{PERM} = 276 \text{ kg P yr}^{-1}$

11. $J_E = \dfrac{4.7 \times 10.5 \times 10^6}{10^6}$

$= 49.4 \text{ kg P yr}^{-1}$

12. $J_{PR} = \dfrac{75 \times 2.68 \times 10^6}{10^6}$

$= 201 \text{ kg P yr}^{-1}$

13. $J_N = 49 + 201$

$= 250 \text{ kg P yr}^{-1}$

14. $N_C = 63$

$N_D = 0$

$\therefore N_{CU} = 63$

15. $J_A = 0.8 \times 63 \times 0.63$

$= 31.8 \text{ kg P yr}^{-1}$

16. $J_T = 250 + 31.8 = 282 \text{ kg P yr}^{-1}$

J_T is $> J_{PERM}$ $(276 \text{ kg P yr}^{-1})$

Therefore, allow no further development to maintain the lake at Level 1.

Calculate how many cottage units would result in deterioration to Level 2.

STEP

1. [chl a] $= 5 \text{ mg m}^{-3}$

2. $\therefore$ [P] $= 18.5 \text{ mg m}^{-3}$

10. $L_{PERM} = \frac{18.5 \text{ X } 19.1 \text{ X } 0.098}{0.18}$

$= 192 \text{ mg m}^{-2} \text{ yr}^{-1}$

$J_{PERM} = 516 \text{ kg P yr}^{-1}$

13. $J_N = 250 \text{ kg P yr}^{-1}$

$\therefore \quad J_A = 266 \text{ kg P yr}^{-1}$ is allowed

17. $N_{PERM} = \frac{266}{0.63 \text{ X } 0.8}$

$= 528$ cottage units (total)

or an additional 465 cottage units (or 68 permanent dwellings)

What is the expected steady-state concentration of phosphorus in Miskwabi Lake based on the present supply of phosphorus?

$J_T = 282 \text{ kg P yr}^{-1}$

$L_T = 105 \text{ mg m}^{-2} \text{ yr}^{-1}$

$\therefore \quad [P] = \frac{105\ (0.18)}{19.1 \text{ X } 0.098}$

$= 10.1 \text{ mg m}^{-3}$

This compares very favourably to the measured concentration of 11 mg m^{-3}.

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